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mulation of the Changes in bundance of the Cod *(Gadus morhua* L.*)* nd the Distribution of Fishing the North Atlantic

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Author's Note

This report was first written in 1968 and is based on data which were available at that time. It is not possible to write a report of this kind which is both comprehensive and up to date when published, and this unavoidable time-lag should be borne in mind when reading the paper.

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Abstract

This paper attempts to treat the various cod stocks of the North Atlantic in an integrated manner. Individual population models of the Beverton and Holt type are first produced, predicting the effect of different levels of fishing effort on the separate stocks, e.g. the numbers of cod of various ages likely to be caught, the number left in the stock and the weight of the total expected catch, in metric tons.

National catch and fishing effort statistics on these stocks since 1946 are used to derive estimates of the total national and international catch (in metric tons) and fishing effort (in ton-hours fishing) associated with cod in the north Atlantic.

A computer program is described which simulates the changes in abundance of these cod stocks for each year since 1946. Estimates of the size and composition of the individual stocks in 1946 are used as a starting point, and total national fishing efforts in each month of each year are distributed between the stocks by the program on the basis of the expected catch from each stock by a given nation. The international fishing effort so distributed then interacts with the resources to generate changes in the stocks and catches from them.

Depending largely on the magnitude of recruitment and the amount of fishing applied, each stock is either increasing in numbers, maintaining its abundance, or decreasing in numbers. The more abundant a stock is, the more likely it is to attract fishing effort, which in its turn helps to make the stock less attractive.

The simulation shows that the changes in abundance of the cod stocks in the north-east Atlantic since 1946 can be explained satisfactorily in this manner. The simulation is less accurate for the north-west Atlantic stocks, due in part to insufficient data. A realistic example is given to demonstrate the use of the model in predicting the effect of future changes in fishing effort on the north Atlantic stocks.

ıulation of the changes in abundance of the cod (*Gadus morhua* L.) l the distribution of fishing in the north Atlantic

Introduction

ılied research into fish populations aims first to under- d the significant mechanisms behind population changes then to incorporate them into mathematical models des- ing the size and structure of a population at known es, and under different conditions. Some of these condi- s, for example growth, are functions of the fish and its ıral environment, but others, such as the age at which first become liable to capture, are partially controllable nan.

ne of the most important variables in an exploited fish ulation is the fishing effort exerted on it. Since this is a ıan activity which might be controlled, mathematical dels of populations not only include it as a variable, but usually maximized with respect to it, and it is possible to ıpute a theoretical value of fishing effort for which the ximum possible catch is obtained. The amount of fishing rt giving this maximum possible catch is a statistic that nuch used in fisheries management. The concept of a *ximum sustainable yield* (Beverton and Holt 1957) incor- ates the notion that the maximum possible yield from a k, under the ideal level of fishing, must be able to be ntained without causing an eventual decline of the stock.

ı general, this concept has been applied to individual ks of particular species on the premise that, the stocks ıg biologically independent units, the effect of fishing n one stock will have no influence on the abundance of adjacent one. The advent of technologically advanced ing fleets with increased flexibility in their operation mpts a qualification of this approach, because the events ne stock may now have a very significant influence on distribution of fishing effort, and hence on the abun- ce of adjacent stocks. This is particularly evident in the th Atlantic cod fisheries. This paper presents an approach he solution of this broader problem of optimizing the ribution of fishing effort over a number of biologically ependent stocks.

he paper first establishes a series of deterministic popu- on models for discrete cod stocks in the north Atlantic an, incorporating well-established parameters, viz.:

the growth in weight of individual fish, which is here represented by a series of average weights at integral ages;
the number of recruits, R, entering each stock in each year as young fish from that year's spawning; recruitment is here considered to take place when the fish leave the surface waters in which they spend their first few months of life, and adopt the demersal existence typical of older cod;
the fishing mortality generated in a particular stock by a unit of fishing effort in conjunction with the availability coefficient, q;
a fractional fishing effort, ε, which is an age-specific parameter giving the degree of fishing effort acting upon cod in the intermediate phase of life until they are of sufficient size to be subject to the full fishing mortality incident on the adult in the stock; it takes discrete values for each integral age;
(4) the natural mortality coefficient, M, indicating the level of mortality due to natural (non-fishing) factors.

The next step has been to attempt to unify the north Atlantic complex of cod fisheries. By treating the international fishing effort in the north Atlantic as sufficiently mobile to be applied to any of the north Atlantic cod stocks, the fishing effort may be distributed among the stocks on the basis of the expected catch from each. Furthermore, it is possible to simulate the dynamic relationship between fish abundance and fishing effort, in which a favourable catch-rate at any stock attracts a considerable amount of fishing effort from the others, with a subsequent high mortality and loss of attractiveness of the heavily fished stock, and corresponding further changes in the pattern of exploitation of them all.

It is therefore possible to visualize the north Atlantic fish/fishery interaction as a dynamic situation, held in its state of balance or imbalance by the distribution of fishing effort between the stocks. The basic biological characteristics of the different stocks are the weighting factors affecting the distribution and spread of the different fishing fleets.

The use of deterministic parameters as a basis for the model imposes an inevitable lack of flexibility on the theoretical population. In particular, there is no allowance in the model for any variation, determined or random, with time of the values chosen for the parameters. This prohibits, for example, any change in the values of fractional fishing effort to accord with the mesh regulations imposed since 1946. If it was discovered, by experimenting with different values of a parameter, that an increasing or decreasing function of that parameter with time would be more appropriate, this may be achieved by incorporating in the model parameters describing the function.

Treating the north Atlantic cod fishery as a stock complex has the advantage of tackling a composite situation as it exists, rather than one stock at a time, as has previously been done. It may be possible to hypothesize the multiple effects on a number of stocks of the movement of effort, and optimum levels of fishing may be suggested for each stock and the north Atlantic as a whole. Arising from this, it may be possible to identify which biological characteristics are the principal determinants, and measures might be suggested to restrict the economically inevitable movement of fishing effort on to a stock at a time that is unsuitable in a long-term sense, for example when the appearance of a strong year-class of young cod in any one stock may be sufficient to attract an excessive level of fishing effort.

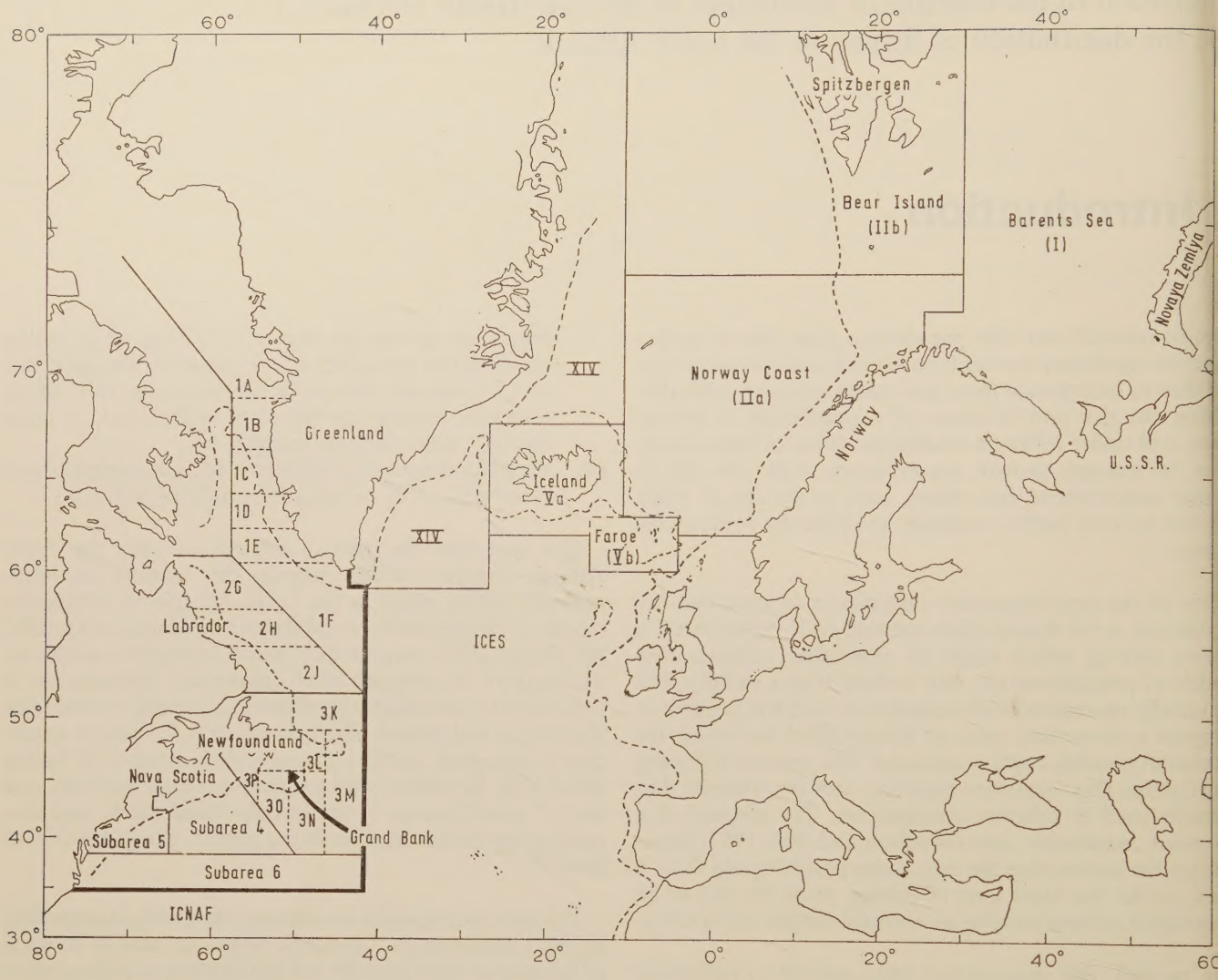


FIG. 1 ICNAF and ICES geographical divisions in the north Atlantic, and the 300 fathom depth contour.

Stocks of Cod and the Cod Fisheries of the orth Atlantic

is section, the presence and location of a number of ively discrete cod stocks is established, together with the of the international catches taken from them since 1946. major fishing nations exploiting these stocks are iden-, and the amount of fishing effort applied by these ons to the different stocks is given. By comparing the es resulting from the application of varying amounts ese national units of fishing effort, each such unit is ex-sed in standard terms. In this way, the national and national effort on each stock separately, and on all e of the north Atlantic, is given in terms of a standard of effort.

sing the catch and standardized effort statistics, changes e abundance of the stocks are described, so that the ionships between the abundance and the amount of ng effort applied may be quantified.

IDENTIFICATION OF DISTINCT STOCKS

order to understand the complex cod stock situation in north Atlantic Ocean, it is necessary to divide all the cod ent into a number of *unit stocks*. A unit stock is defined population which is independent of all other stocks, by ue of having no emigration to, or immigration from, r areas; i.e., the adult fish in that stock remain in that throughout their life, never mixing with individuals other stocks, and spawn among themselves in that , with all their products of spawning developing in that .

he ideal unit stock situation thus defined rarely exists in tice. There must be few absolutely discrete stocks of fish e world having no mixing at all with other populations he same species. A more frequent situation is one in ch seasonal mixing of individuals from different sub-ks occurs (Cushing 1955, Harden Jones 1968). For ex-le, two populations may be completely separate during feeding phase of their annual cycle, but meet during the ding season, when they mix on a common spawning nd (Trout 1957).

agging of cod in different parts of the north Atlantic has wn that, with a few remarkable exceptions, tagged cod ergo either very limited movements, or, in the case of -distance movements, definite seasonal migrations asso-ed with particular phases of their life history, when they e *en masse*, e.g. at spawning. By studying the results of e tagging experiments, and taking into account the hy-graphy of the ocean and other specific information, the h Atlantic cod resources may be divided into a number istinct stocks or groups of interconnected stocks. Figure a map of the north Atlantic, showing the positions of various stocks of cod, together with the 300 fathom h contours.

t this stage it should be mentioned that, although the th Sea is geographically part of the north Atlantic, the re of cod stocks there, and the fishing effort applied to n, make it a separate system, and it is therefore not con-ed here.

The north-east Arctic is divided into three geographical regions—the Barents Sea, the Bear Island area, and the Norway coast area; the first two of these are feeding areas and they support two sub-stocks of cod which intermix in their common spawning area off the Norway coast. Mature cod from the two feeding areas migrate annually southwards to spawn in quite a localized area off the Norway coast (Cushing 1966, Garrod 1967). Each of the three geographical regions supports a large cod fishery. Cod from this Arcto-Norwegian stock, as the whole complex is called, do not appear to mix with cod from other stocks.

Further west another important cod fishery takes place at Iceland. Cod spawned at Iceland have been shown, on the whole, to remain in Icelandic waters (Jonsson 1965). Tagging has however revealed that a number of mature cod emigrate from Greenland to Iceland to spawn, and research is at present in process to determine the extent of this migration (Jonsson 1953, Harden Jones 1968). Certainly some cod caught in the special spawning fishery at Iceland do originate from outside Icelandic waters, and so contribute an unknown amount to the total weight of cod caught at Iceland.

Knowledge of the quantity of fish involved in this migration is essential to the ultimate aim of simulating the total cod fishery at Iceland within the total north Atlantic cod fishery. Since the estimates necessary for this procedure are not known it has been necessary to divide the fishery into two components to reduce the potential errors caused by this uncertainty. These components are the fisheries for non-spawning (almost entirely immature) and spawning cod whose exploitation is effectively separated in time and space and in the nations exploiting them. The fishery for non-spawning cod at Iceland can be regarded as a unit stock from which permanent emigration occurs to the spawning fishery. The spawning fishery itself however cannot be incorporated so readily because of the lack of quantitative estimates of recruitment to it from different sources. This fishery has therefore necessarily been excluded from this initial model. This involves the exclusion of a yield of some 200 000 tons annually and so introduces a measure of unreality which should be borne in mind in interpreting the results. However, as with the exclusion of the North Sea and Gulf of St. Lawrence cod fisheries, the exclusion of the Iceland spawning fishery does not impair the utility of the model itself since the characteristics of the fishery do maintain its isolation from the remainder of the fisheries considered here as a single system.

Further south the shallow water round the Faroe Islands supports two small, but distinct, cod stocks, the Faroe Plateau stock and a smaller one, the Faroe Bank stock (Jones 1966, Jamieson and Jones 1967), which are separated by a channel of deeper water. Tagging experiments have shown that very little intermixing takes place between them, and other research investigations have shown that the two stocks have very different growth characteristics. They should therefore be regarded as separate stocks but in view of their relatively small importance in the context of the north Atlantic as a whole, and because the Plateau stock contains 80–90 per cent of the cod in this area, they have here been combined.

The general pattern of identification followed for the north-west Atlantic stocks is that described by Templeman (1962), though it is evident that the distinction between some of the stocks is less clear than it is for the north-east Atlantic stocks. There are considered to be three stocks of cod at Greenland:

(1) the north-west Greenland stock (ICNAF subareas 1A–1D);
(2) the south-west Greenland stock (ICNAF subareas 1E–1F);
(3) the east Greenland stock (ICES region XIV, but here included with the north-west Atlantic stocks).

This separation is made primarily on the basis of experiments in which mature cod were tagged at Greenland (Hansen 1949, 1953). In addition to their discrimination between stocks at Greenland, these experiments also indicated the contribution of these stocks to the spawning at Iceland referred to earlier. Recaptures at Iceland fell into several groups, with east Greenland contributing most to the spawning migration to Iceland, and south-west Greenland contributing an amount intermediate between east Greenland and north-west Greenland. This, together with the differe growth rates of cod in these regions (see Section 3, Table and different meristic characters (particularly the number vertebrae and the number of fin rays), confirmed the esse tial discreteness of the three stocks (Tåning 1938, Bevert and Hodder 1962).

The shallow waters off Labrador and Newfoundland su port a further two large stocks. The more northerly of the is referred to as the Labrador/Newfoundland stock, livi in ICNAF subareas 2G, 2H, 2J and 3K, while the other, t Grand Bank stock, occupies ICNAF subarea 3, divisions N and O. There are additional, partially independent co stocks in subareas 3M, 3P, and in subareas 4 and 5 whic have been omitted entirely from this exercise, because t size of their contribution to the north Atlantic cod catch not great, and their complex inter-relationships, one wit another, are not fully understood at this time.

TABLE 1 *The average percentage composition by species and stock of the international fish catch*

	Percentage of							Total % accounted for	Total catch of all species (thousand tons
	cod	haddock	redfish	saithe	capelin	herring	flounder		
(a) North-east Atlantic stocks, 1947–66									
Barents Sea	57.7	12.8	2.3	5.0	4.6	7.0		89.4	563
Norway coast	24.3	3.2	1.2	9.5	0.8	54.6		93.6	1152
Bear Island	80.0	3.7	8.5					92.2	158
Iceland	43.5	7.3	7.4	6.8	0.7	24.3		90.0	979
Faroe	35.6	22.6	3.0	13.5		9.0		83.7	83
(b) North-west Atlantic stocks, 1955–66									
North-west Greenland	88.2		6.0		0.2			94.4	298
South-west Greenland	81.6		15.3				0.5	97.4	74
East Greenland	31.8	0.3	51.7	1.0		5.9		90.7	64
Labrador/Newfoundland	82.2		14.0		0.1			96.3	326
Grand Bank	69.8	9.6	8.2	0.1	0.3	0.2	8.4	96.6	361
ICNAF subarea 4	35.6	9.2	9.9	2.5		9.4	4.5	71.1	589
ICNAF subarea 5	3.8	11.3	2.5	0.7		9.5	5.6	33.4	580

2.2. THE COD FISHERIES

(a) *Total international catch*

Table 1 gives the average percentage composition of the total international catch of the principal species from each named stock area, with those from ICNAF subareas 4 and 5 given for comparison. The averaging of such figures over periods of up to 20 years has meant that some of the percentages may be misleading. For example, large-scale fishing for capelin in the north Atlantic only started in 1961, and in the Barents Sea the percentage of capelin in the total fish catch has varied from less than 1 per cent to 33 per cent, giving a 21-year average of 4.6 per cent. Similarly, although herring have been fished in the north Atlantic for a much longer period, the amount caught in any one year has varied widely during that time. Both capelin and herring are usually caught by gill-nets, purse-seine or pelagic trawl when they are swimming off the bottom of the sea. So far they have never been caught in quantity together with cod, and their significance with respect to fishing effort applied to demersal fish is negligible.

It may be seen that demersal fish make up 85–90 per ce of the total (all species) catch in all the north-east Atlant stocks except Norway coast, where the figure is 40 per ce because of the large catches of herring and (more recentl capelin.

Table 1 also shows that within the demersal fisheries co haddock, redfish and saithe are the four most importa species, and of these cod itself forms the largest single sha of the demersal catch in all of the chosen stock areas exce east Greenland. Even there, where redfish predominate the catch, approximately one-third of the total is cod, a redfish and cod together provide an average of more th 80 per cent of the total catch.

The figures for subareas 4 and 5 show the decreasing i portance of cod in the total catch as the southernmost lin of the cod's distribution is approached. Haddock, redfi and flounders become more important, as well as the vario types of hake (not shown in Table 1). In subarea 6, fi recognized by ICNAF in 1966, scarcely any cod at all a caught.

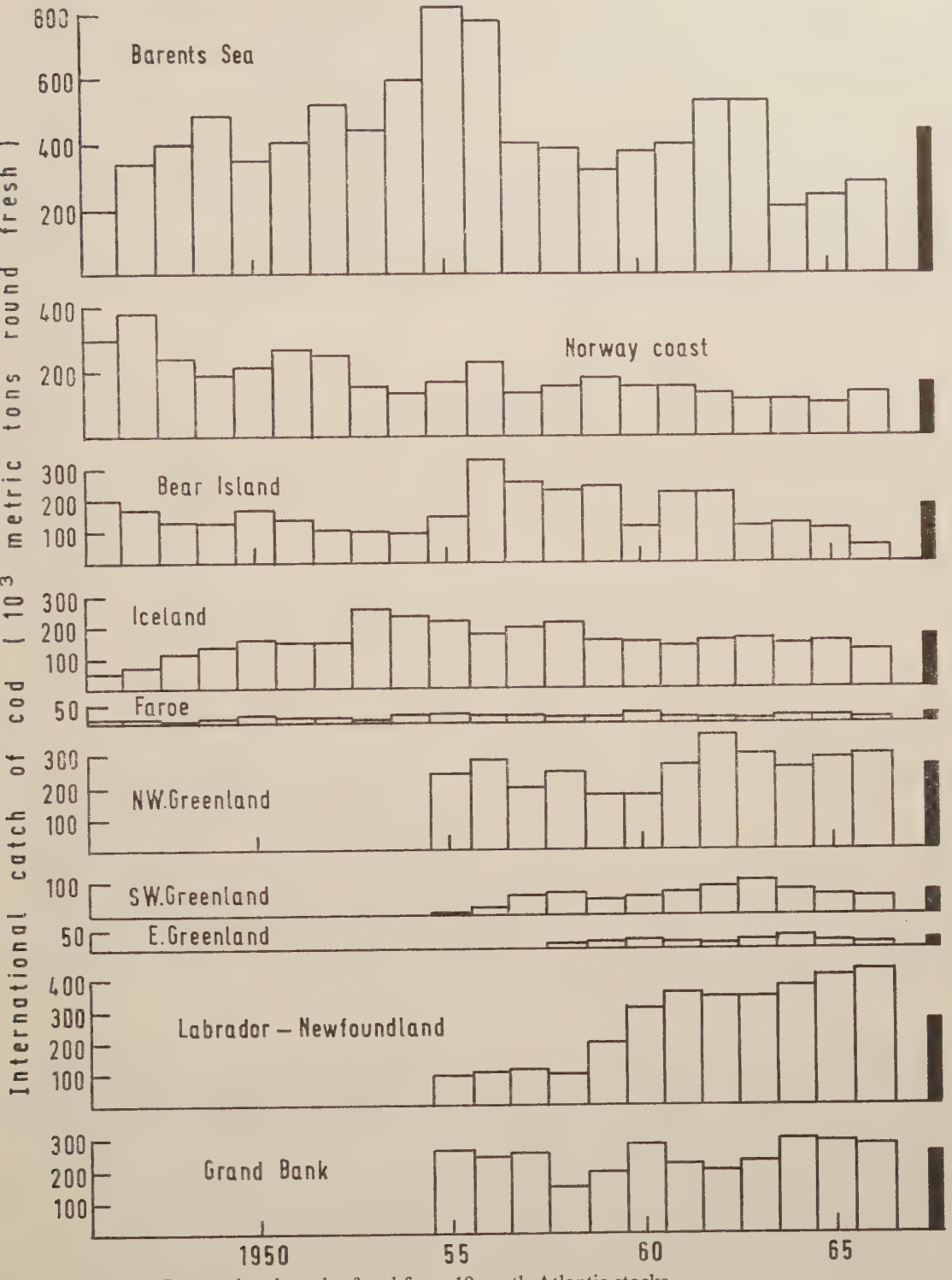


FIG. 2 International catch of cod from 10 north Atlantic stocks.

Figure 2 shows the annual international catch of cod from h of the named stocks for each year available since 1946, actual data being given in Appendix 1. Figures for the th-west Atlantic stocks commence only in 1955, because hough a considerable amount of fish was caught in the th-west Atlantic during the years 1946–55, full details not available (ICNAF Working Group Report 1962): 5 was considered to be the first year in which relatively nplete catch and effort statistics existed.

There is considerable variation in the catch from each ck over the years, partly as a result of changes in the ount of fishing and partly as a result of variation in the of year-broods. At the right-hand side of Figure 2 is a giving the average catch of cod from each stock during the period 1955–66 (in the case of east Greenland, for the period 1958–66); these are given so that the relative sizes of the different stocks during that period may be established. Thus it may be seen that Faroe, south-west Greenland and east Greenland are relatively unimportant in terms of their contribution to the whole north Atlantic catch. The Arcto-Norwegian stock complex contributed an average of 40 per cent of the total north Atlantic catch, while the three large north-west Atlantic stocks each contributed about 15 per cent. The catch of cod at Iceland given in Figure 2 does not include the yield from the large spawning fishery, carried out chiefly by the Icelanders, which over the same period contributed 260 000 metric tons (m tons) per year (approximately one-and-a-half times the weight of cod caught in the non-spawning fishery).

It may be calculated that the five north-east and five north-west Atlantic stocks identified in Figure 2 provide an average of 88 per cent of the total north Atlantic cod catch.

(b) *National participation in the cod fisheries*

Many nations operate fishing fleets in the north Atlantic, although a small number take the majority of the catch. For the purpose of this study 10 nations have been identified as fishing widely throughout the north Atlantic, viz.: England, USSR, Federal Republic of Germany, Norway, France, Portugal, Spain, Faroes, Scotland and Belgium. In mo stock areas there is also an important inshore component the fishery, for example the Norwegian fishery off Norwa and the large Canadian inshore fishery in ICNAF subarea 2 and 3. Typically these are lining, gill-net and trap-n fisheries carried out by a large number of small boats. the north-west Atlantic where these inshore fisheries are n pursued by one of the named countries the catches ha been assigned to a *dummy nation* for convenience of furth analysis, together with the small catches of a number other countries which make a relatively insignificant contr bution to the total fishery.

TABLE 2 *Average catch of cod (10^3 metric tons) by each nation, from north Atlantic stocks (1955–66)*

	Barents Sea	Norway coast	Bear Island	Iceland	Faroe	Greenland			Labrador/ Newfoundland	Grand Bank	Total (10 stocks)
						NW	SW	E*			
England	56	23	71	122	8	6	7	1	3	5	302
USSR	245		72			1	<1		38	14	370
Germany	3	10	5	29	1	46	15	14	11	1	135
Norway†	109 (+31)	112 (+2)	20 (+12)	4		23	12			4	284 (+45
France	<1			<1		33	1		37	13	84
Portugal						73	5		51	44	173
Spain						9	1		39	61	110
Faroe	<1			11	8	54				8	81
Scotland				3	11						14
Belgium				6							6
Dummy 1						17					17
Dummy 2							24				24
Dummy 3								5			5
Dummy 4									90		90
Dummy 5										97	97
Total (all nations)	444	147	180	175	28	262	65	20	269	247	1837

* Figures averaged over 1958–66.
† Figures in parentheses represent the small catch taken by other nations, e.g. France and Faroe.

Table 2 identifies the 10 nations taking the most cod from the north Atlantic, and gives the average annual catch for 1955–66 by each of these nations from each stock. The five dummy nations are also given, each with their catch assigned to one of the five north-west Atlantic stocks. The catch from dummy nations 1 and 2 refers largely to the Greenlanders' inshore fishing, whereas the catch from dummy nation 3 refers both to the Greenlanders' and Icelanders' fishing. The catch from dummy nations 4 and 5 refers principally to the Canadian (Newfoundland) inshore fishery, but also includes catches taken by nations such as Poland, Rumania, Italy, France (St. Pierre and Miquelon) and any unassigned catch (non-members of ICNAF).

Generally speaking, for the north-east Atlantic stocks a higher proportion of the total yield can be attributed to the 10 nations. The small amount taken from the Arcto-Norwegian stock by nations such as France and Faroe is included for simplicity in the catch assigned to Norway, and is displayed in Table 2 in parentheses. At Iceland, the Icelanders have a strong inshore fishery, but this is aimed primarily at the spawning cod, which have been excluded from this study. Apart from the Icelanders, France and Holland also catch very small quantities of cod at Iceland.

Of the 10 identified nations, England, USSR, Germany and Norway fish throughout the north Atlantic, taking a average of 60 per cent of the total north Atlantic cod catc of nearly 2 million metric tons between them in the perio considered. France (Maritime), Portugal and Spain fish a most entirely in the north-west Atlantic, taking an averag of 40 per cent of the cod caught there. The Faroese fish widel throughout the north Atlantic, but mainly at Greenlan Iceland and Faroe. Excluding the North Sea, the Scots fis only at Iceland and Faroe, and Belgium fishes only at Ic land, these latter two nations taking only about one per ce of the total north Atlantic catch between them.

The cod are caught with a variety of fishing gears. T modern fishing fleets of many nations, e.g. England, Ge many, USSR, consist largely of technologically advanc otter-trawlers, able to catch large quantities of cod a freeze them at sea. Other fleets, such as those of Portug Spain, Norway and Faroe, rely on lining to a greater exte Table 3 compares the amount of cod caught by the differe fishing gears in the ICNAF subareas 1, 2 and 3 duri 1955–60. This shows that the otter-trawl is the most i portant gear, with dory vessels second in importance. Pa trawling is carried out principally by Spain on the Gra Bank stock. The total for subarea 3 under *miscellaneo gears* is caught mainly by the inshore fishery.

LE 3 *Catch of cod (10³ metric tons) assigned to different gears in ICNAF subareas 1, 2 and 3*

	1955	1956	1957	1958	1959	1960
Subarea 1						
Otter-trawl	128	178	140	171	108	99
Pair-trawl	–	–	–	–	–	–
Dory vessel	64	71	75	72	52	61
Hand-line/long-line	53	51	30	50	45	41
Miscellaneous	20	21	25	26	28	40
Total	265	321	269	319	234	241
Subarea 2						
Otter-trawl	15	26	20	29	41	133
Pair-trawl	–	–	–	–	–	–
Dory vessel	–	–	–	–	–	–
Hand-line/long-line	–	–	–	–	–	–
Miscellaneous	11	8	12	11	19	17
Total	26	34	32	40	60	150
Subarea 3						
Otter-trawl	171	104	162	96	160	123
Pair-trawl	29	37	38	30	39	45
Dory vessel	50	50	48	23	32	39
Hand-line/long-line	4	1	23	16	17	18
Miscellaneous	174	190	178	128	177	184
Total	429	382	449	293	425	408

National and international fishing effort

n order to be able to treat the north Atlantic Ocean as a plex of cod stocks, fished by a number of nations, it is essary to develop unified estimates of fishing effort within between stocks and nations. Within each of the 10 ons and 5 dummy nations fishing the north Atlantic e may be a number of types and categories of fishing el, each with its own cod-catching characteristics. The step in developing a unified measure of fishing effort to establish the *relative fishing power* of each category essel in terms of one standard type of vessel.

he relative fishing power of a vessel is defined here as weight of fish (in this case, cod) caught per unit of fishing rt compared with the amount caught by the standard el, when the abundance of the fish is identical.

Gulland (1956) gives the equation:

$$C_{ij} = q_j.\alpha_i.t_{ij}.d_j.E_{ij}, \qquad (2.1)$$

ere C_{ij} is the catch taken by the ith gear on the jth occasion;

q_j is the availability on the jth occasion;

α_i is the relative fishing power of the ith gear;

t_{ij} is the time spent fishing by the ith gear on the jth occasion;

d_j is the density of fish on the jth occasion;

E_{ij} is the random error.

occasion is here taken as a situation in which the fishing rs being compared fished the same stock in the same r. The catch (C_{ij}) and fishing time (t_{ij}) being compared the annual summations on each stock by each gear. Reanging Gulland's equation gives:

$$\frac{C_{ij}}{t_{ij}} \cdot \frac{1}{E_{ij}} = (q_j.d_j)\alpha_i = K_j.\alpha_i, \qquad (2.2)$$

ere K_j is constant for each occasion, and $\frac{C_{ij}}{t_{ij}} = \left(\frac{C}{t}\right)_{ij}$

he catch per unit time spent fishing by the ith gear on jth occasion.

When two fishing gears, a standard gear (s) and another gear (i), fish together on a number of occasions, the sets of paired values of $\left(\frac{C}{t}\right)_s$ and $\left(\frac{C}{t}\right)_i$ allow the estimation of α_i:

$$\left[\left(\frac{C}{t}\right)_s \cdot \frac{1}{E_s}\right]_j = \left[\left(\frac{C}{\alpha_i t_i}\right) \cdot \frac{1}{E_i}\right]_j = K_j \quad i \qquad (2.3)$$

i.e. a least-squares regression line passing through the origin may be calculated, such that:

$$\left(\frac{C}{t}\right)_i = \hat{\alpha}\left(\frac{C}{t}\right)_s \text{ for all values of j.} \qquad (2.4)$$

Then, $t_s = \hat{\alpha} t_i$.

α is prone to bias because the distribution of $\frac{1}{E_{ij}}$ is non-normal. Moreover, the amount of fishing effort involved in the annual values of catch per effort may vary tremendously. For example, in comparing the French 900–1800 tons otter-trawler (OT) catch per day's fishing and the English 500–900 t OT catch per hour's fishing the annual fishing efforts varied from 40 to 2000 days' fishing, and 500–16 000 hours' fishing respectively. The estimates of catch per effort obtained from these different amounts of fishing are likely to vary in their accuracy.

Because of these sources of error, the estimates of the slopes obtained from the regressions were only used when the two sets of catch-per-effort being regressed were significantly correlated; when comparing two types of fishing gear with similar units of effort (e.g. hours' fishing), the slope estimate used was unity, unless it could be shown to be significantly different.

The technique followed was first to compare all the categories of fishing gear within each nation's fleets with the most important gear of that nation. In this way the total

fishing effort of each nation was expressed in terms of one of that nation's units of effort. Applying this to the English fisheries, for example, the three categories of English gear units were put in terms of the 500–900 t OT hours' fishing. There were 22 and 30 occasions respectively when the 500–900 t English trawlers fished the same stock in the same year as the 900–1800 t freezer trawlers and the 1800+ t factory trawlers. The following estimates were obtained (with 95 per cent confidence limits): 1 hour's fishing by 900–1800 t OT = 0.79 hour's fishing by 500–900 t OT ± 0.32, and 1 hour's fishing by 1800+ t OT = 0.90 hour's fishing by 500–900 t OT ± 0.32. Figure 3 shows the regression obtained from the scatter diagram for the first of these comparisons. Estimates for both comparisons were significantly different from zero, but neither was significantly different from unity. For this reason, the hours' fishing by the three gears are added directly to give the national fishing effort in English 500–900 ton-hours' fishing.

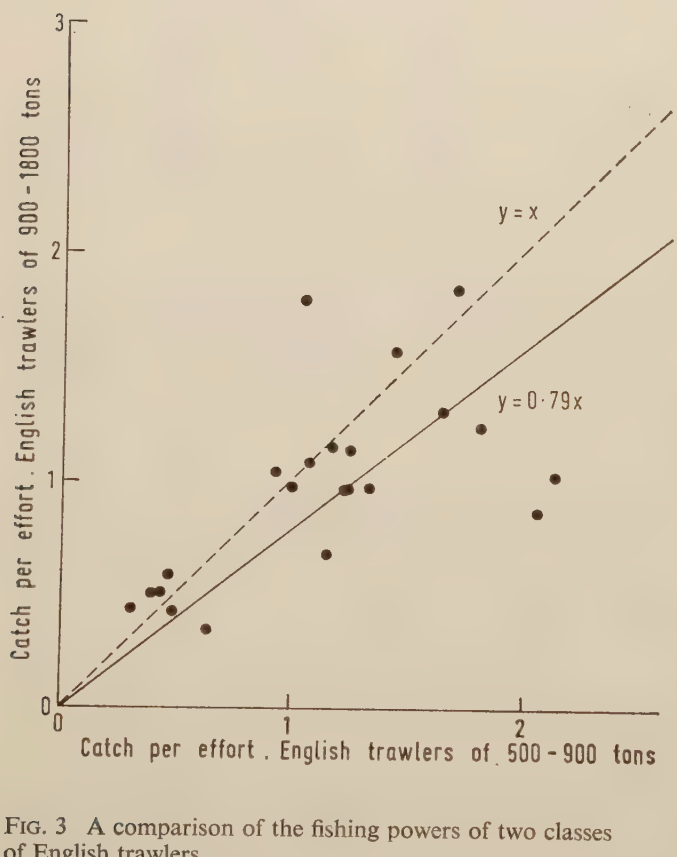


FIG. 3 A comparison of the fishing powers of two classes of English trawlers.

Having repeated the above process for all countries, the total catch of a nation by all its fishing gears was divided by the total fishing effort of that nation, expressed in terms of units of one of its gears, to give the resulting national values of catch-per-effort found in Appendix 2. These values were then compared with the values of a fleet where effort could be measured in standard units of fishing effort. The hours' fishing by English side trawlers of 500–900 t was chosen as this standard because, of all the fleet categories available, this has fished the most widely for the longest period and hence permits the greatest number of direct comparisons between fleets. Where both the standard gear and the one to be calibrated fished the same stock in the same year, the two values of catch-per-effort are in the same column in Appendix 2. The set of these paired observations was then regressed as before, resulting in factors for the conversion of each national gear unit to the standard unit as given in Table 4.

In this way, the effort data of most of the 10 major nation fishing the north Atlantic have been expressed in terms the single standard unit of effort, but the complexity of th fisheries means some inevitable gaps in the calibration. Fo example, the catch and effort data of Norway and Faro come from a variety of fishing gears, used on a number the north Atlantic stocks, and it proved impossible to ex press their long-line, hand-line, gill-net, purse-seine an otter-trawl units of effort in terms of the standard unit. Th five dummy nations, each fishing one of the five north-wes Atlantic stocks, are in a similar position, having complet catch data, but insufficient or mixed effort data. In the case of Norway, Faroe and two of the five dummy nations, i was assumed that the English catch-per-effort values wer correct, and the effort values were calculated as follows:

$$\text{Estimated effort by the nation (English units)} = \frac{\text{Known catch of the nation}}{\text{English catch-per-effort}}$$

(Garrod 1967). This is a raising technique, and it estimates the effort by a nation whose catch is known, as the effor that English trawlers would have to apply to obtain th same catch.

At east Greenland, Labrador/Newfoundland and Gran Bank, the English fleet takes a very small proportion of th catch; in some years, no effort at all was applied to some o these stocks by the English fleet. For these three stocks, th catch-per-effort obtained by the German, French and Spanish fleets respectively was taken as the best estimate, converte to catch per English hour fishing, and used in the above equation.

Appendix 1 gives the catch of each nation, and any re maining unassigned catch, for each stock and each year From this, the annual amount of fishing effort executed by Norway, Faroe and the five dummy nations may be esti mated in terms of the standard unit of effort.

So far, no allowance has been made for any increase in efficiency of fishing vessels with time. Gulland (1956) showed that, within the categories of trawler considered (150–900 gross t), catching power was related to several physical attri butes of trawlers, of which the most convenient and accurate was the gross tonnage. It was found that catching power was roughly proportional to gross tonnage. Thus a trawler of 600 t gross weight would be expected to catch approxi mately twice as much as a trawler of 300 t. This relationship is not likely to hold true for trawlers larger than 900 t, whose greater size is related to their fish-storing and freezing capa city and not their fish-catching ability.

In the north Atlantic, the average tonnage of conven tional English trawlers has increased considerably since 1946. The size of trawlers fishing each ground, and the rate at which the average size has increased since 1946, depends on the ground fished, with the larger trawlers tending to visit the more distant stocks. Figure 4 shows that in the north-east Arctic, the gross tonnage has increased from about 500 to 700 t since 1946 (40 per cent in 20 years). A Iceland, trawlers have increased from about 400 to 600 since 1946 (50 per cent in 20 years). The smaller middle water English trawlers visit Faroes, and their tonnage has increased from 250 to 400 t since 1946 (60 per cent in 20 years).

Data from the ICNAF area are less numerous but they indicate that the tonnage of English conventional trawlers has increased from about 700 to 800 t since 1955 (15 per cent in 10 years). The average tonnage of vessels fishing on

TABLE 4 *Comparison of the different units of national fishing effort*

Nation	Type of fishing gear	Units of fishing effort	Number of points used in regression	Significance of regression (%)	L.S. estimate of slope (± 95% limits)	Significance of slope estimate from 1 (%)	Number of points used in regression	Significance of regression (%)	L.S. estimate of slope estimate from 1 (%)	Significance of slope estimate from 1 (%)	Conversion factor to English 500–900 O.T. hours' fishing
England	(500– 900) O.T.	Hour fishing			1.000						1.00
	(900–1800) O.T.	,, ,,	22	99.9	0.793±0.318	NS					1.00
	(1800+) O.T.	,, ,,	30	99.9	0.904±0.324	NS					1.00
France	(900–1800) O.T.	Day fishing					32	99.9	20.550±10.870	S	20.55
Portugal	(150– 500) D.V.	Day on grounds	19	99.9	6.433±1.990	99.9					6.43
	(500– 900) D.V.	,, ,, ,,	23	99.9	8.324±1.715	99.0					8.32
	(900–1800) D.V.	,, ,, ,,	23	99.9	10.996±5.376	S					11.00
	(900–1800) O.T.	Hour fishing			1.000		36	99.0	1.497± 1.052	NS	1.00
Germany	(500– 900) O.T.	Day fishing			1.000		104	99.9	11.510± 2.530	S	11.51
	(900–1800) O.T.	,, ,,	16	99.9	1.110±0.443	NS					11.51
	(1800+) O.T.	,, ,,	7	99.9	1.175±0.764	NS					11.51
Spain	(150– 500) P.T.	Hour fishing	12	98.0	1.011±0.772	NS	33	99.0	1.168± 0.789	NS	1.00
	(900–1800) O.T.	,, ,,			1.000						1.00
USSR	(150– 500) O.T.	Hour fishing	6	NS	0.409±0.848	NS					1.00
	(500– 900) O.T.	,, ,,			1.000		60	99.9	0.867± 0.358	NS	1.00
	(900–1800) O.T.	,, ,,	6	NS	1.265±1.642	NS					1.00
	(1800+) O.T.	,, ,,	8	99.0	2.695±1.723	90.0					2.70
Scotland	(500– 900) O.T.	Hour fishing			1.00		34	99.9	0.478± 0.104	99.9	0.48
Belgium	(500– 900) O.T.	Hour fishing			1.000		13	95.0	0.242± 0.229	99.9	0.24

NS=not significant.
S=significant.

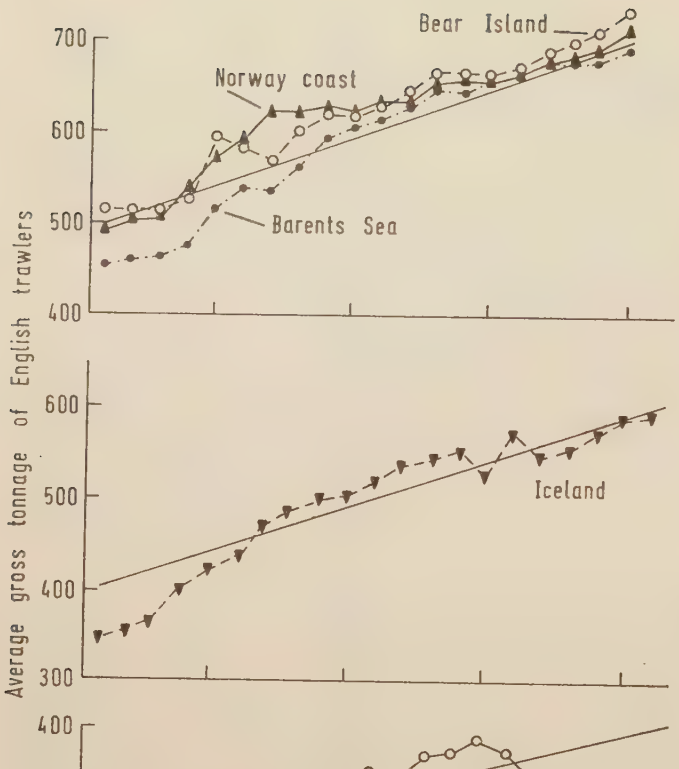


FIG. 4 The increase in average gross tonnage of conventional English trawlers between 1946 and 1966.

any stock in any year has been estimated from straight lines drawn through the upper and lower tonnage limits just mentioned.

The assumption that average tonnage, and thus efficiency of fishing vessels, has increased linearly with time results in an allowed increase of efficiency of between 2 and 3 per cent per annum. By assuming further that all the nations' fishing fleets have increased their efficiency at the same rate as the English fleet, the numbers of standard English 500–900 t otter-trawler hours' fishing carried out by each nation (and each dummy nation) may be multiplied by the average tonnage of English trawlers in that area in that year to give total fishing effort in terms of ton-hours. These figures are given in Appendix 3. Figure 5 gives the total international fishing effort (in million ton-hours' fishing) on each stock since 1946 (1955 for the north-west Atlantic stocks).

Justification for some of these values of international fishing effort, which were obtained by adding that of each nation, may be seen in Figure 6. Here they are compared with values that have been used internationally (ICES 1969, 1970). The correlations are all significant at the 99.9 per cent level, and for the three Arcto-Norwegian stocks the points lie approximately on the line of parity. In the case of Iceland, the points lie on a straight line with a slope of approximately 0.40, because the values used by that particular group refer to the entire Icelandic stock of cod, including the very large spawning fishery that has been omitted from this study. The fact that the points lie on a regression line through the origin shows that the patterns of development of fishing effort with time are similar.

Figure 7 shows the separation into north-east and north-west Atlantic effort. Since 1946 the fishing effort in the north-east Atlantic has risen from 350 to 1400 million ton-hours, a 400 per cent increase in 20 years, reaching a peak in 196[illegible]. During the mid-1960s this effort fell slightly and stabilized, though there has been a subsequent rapid increase in effort again in 1969–70 (Garrod, pers. comm.). The effort in the north-west Atlantic shows a steady rise throughout the period 1955–66, from 300 to 700 million ton-hours. The total effort for the whole north Atlantic reflects the north-east Atlantic picture. The percentage of total effort going to the north-west Atlantic stocks has increased from 25–30 per cent in 1955 to 35–40 per cent in 1966.

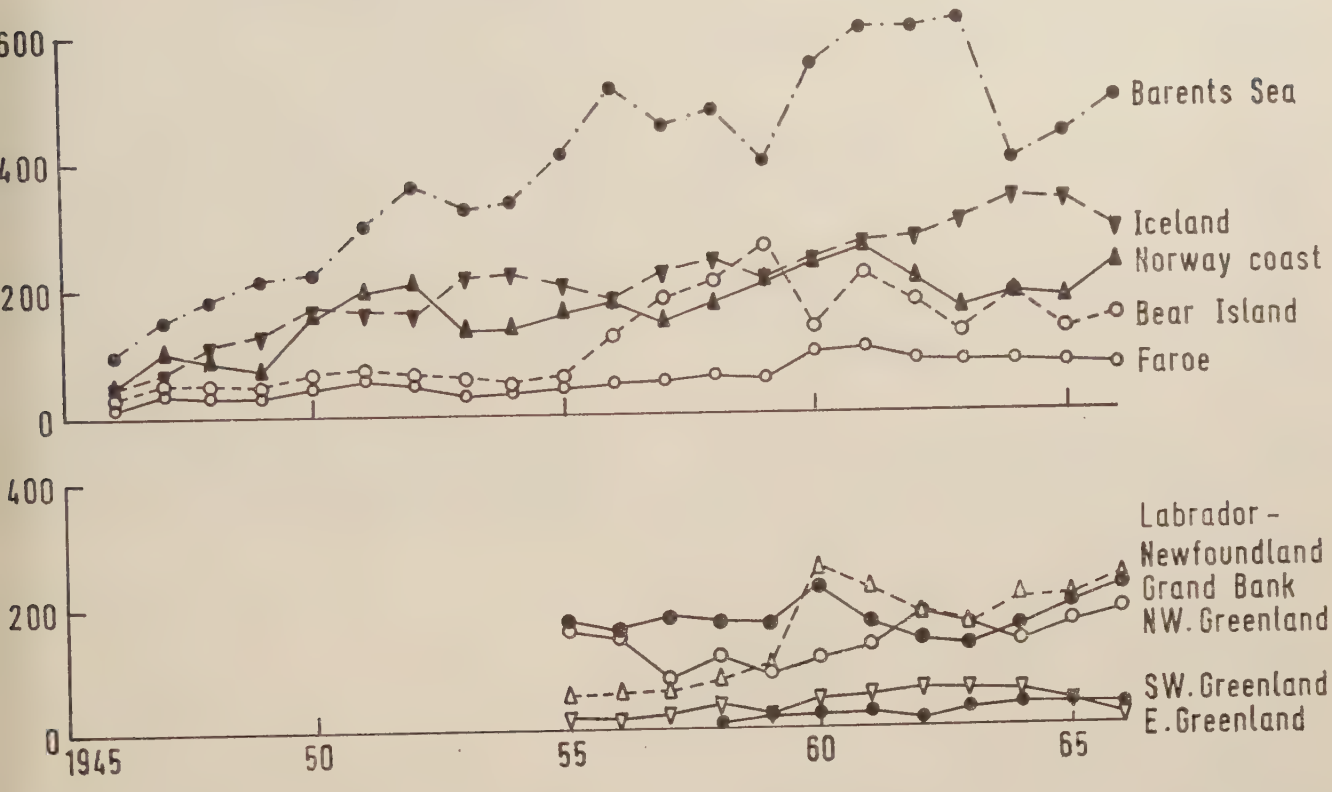
Using the data on which Figure 2 is based, it may be seen that the relative importance of the north-west Atlantic in terms of the total catch of cod has increased since 1955. The percentage of the cod catch from the 10 stocks of Figure [illegible] coming from the five north-west Atlantic areas shows an increase from 30 per cent in 1955 to 50–55 per cent in 1966, i.e. at that time the north-west Atlantic provided more than half the total cod catch from the north Atlantic for approximately 40 per cent of the effort.

Figure 8 shows the relative importance, with respect to effort, of the different nations. They may be considered in two groups, the first of which contains nations fishing most or all of the 10 stocks. Of these, England, USSR and Federal Republic of Germany are the most important, having increased their effort regularly throughout the post-war years by between 7 and 25 million ton-hours' fishing per annum (excepting the great increases in fishing by USSR during 1960–63). The second group of nations is those fishing the north-west Atlantic almost exclusively. Of these, Portugal, Spain and France are the most important, having increased their effort by between 3 and 5 million ton-hours' fishing per annum.

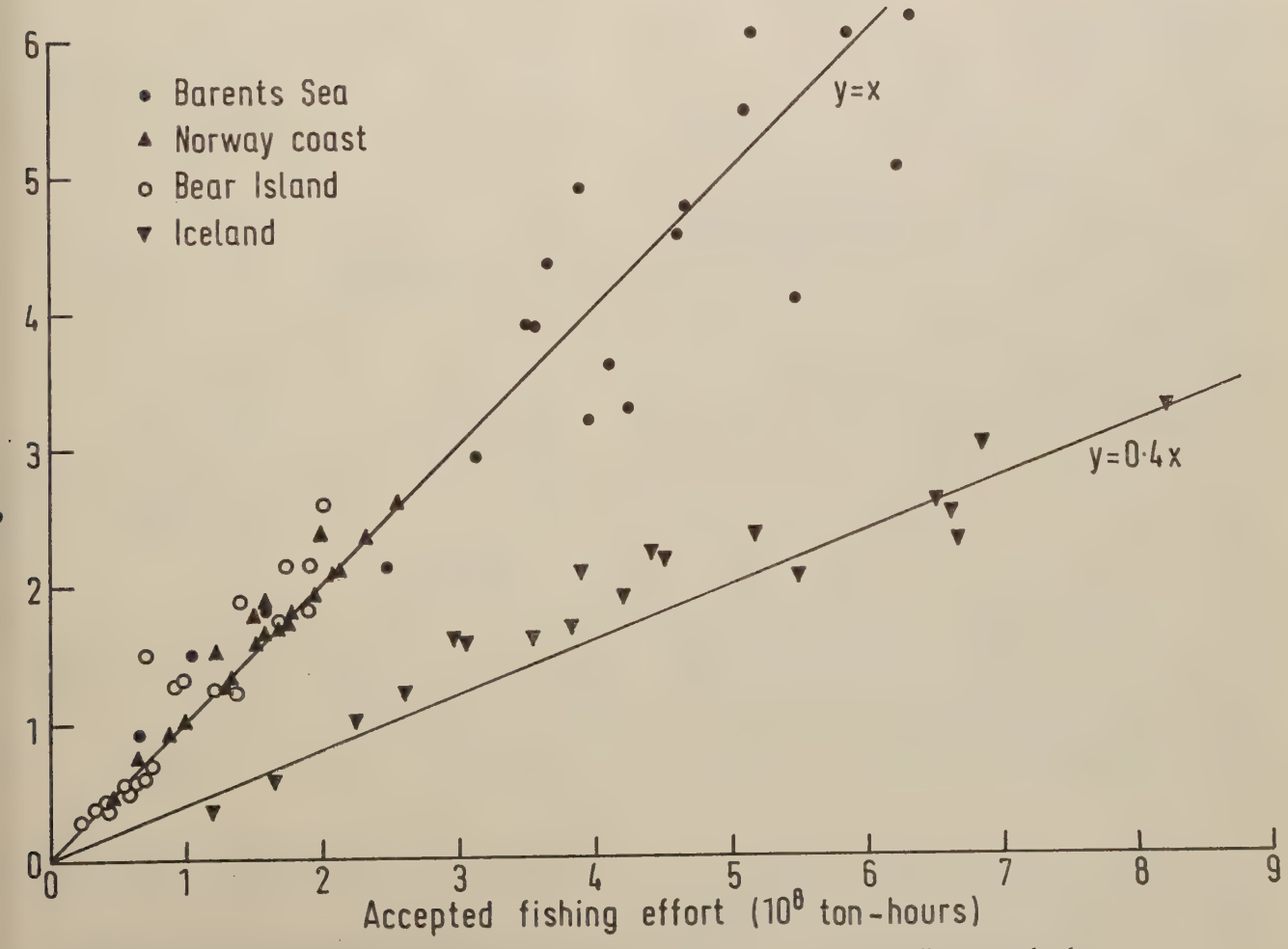
A number of important nations have been left out of this part of the analysis. Faroe and Norway catch a very large amount of cod over the whole north Atlantic, but the previously mentioned difficulties with national effort units have prevented their being considered separately. Other nations such as Canada (Newfoundland), Greenland and Iceland do not have sufficient effort details to include them here: some, such as Belgium and Scotland, are of minor importance in the context of north Atlantic fishing, and others of recent entry into the fisheries, e.g. Poland, have been omitted at this time.

2.3. CHANGES IN ABUNDANCE IN THE NORTH ATLANTIC COD STOCKS

In order to manage a fish stock, in an economic sense, it is necessary to assess whether the stock is changing in any respect with the passage of time, so that these changes may be correlated with factors such as the amount of fishing. In particular, it is essential to be able to detect any change in the actual numbers of fish, and the proportion of fish of different ages, present. The absolute number of fish present in a stock at one time can never be known directly, and instead the catch-per-unit-effort of the commercial fleet is used as an index of this abundance (Beverton and Holt 1957). This index may vary between years owing to longer-term changes in the stock structure, or it may vary within years following seasonal changes in the availability of fish to the fishing gear.



5 The international fishing effort on 10 north Atlantic cod stocks.



6 A comparison of the predicted fishing effort values used in this paper with internationally accepted values.

FIG. 7 International fishing effort in the north-east and north-west Atlantic (1946–66).

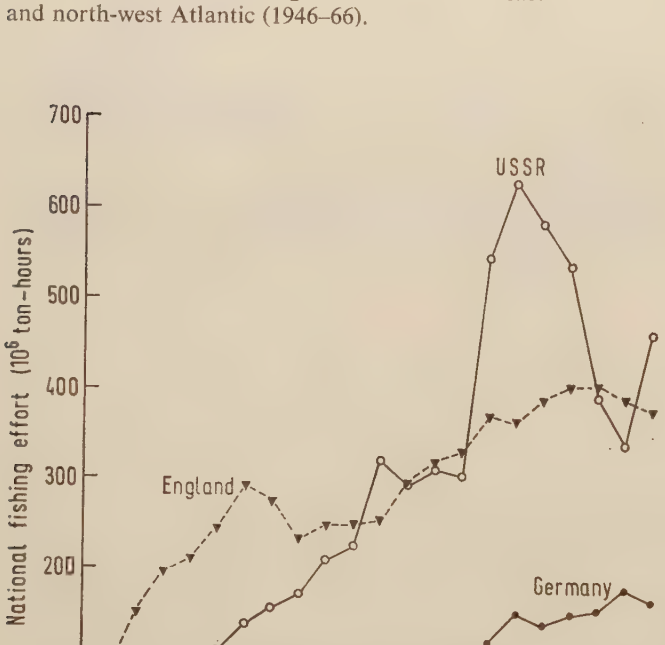


FIG. 8 National fishing efforts in the north Atlantic (1946–66).

(a) *Fluctuations in abundance between years*

Figure 9 gives the catch-per-effort (in metric tons round fresh per million ton-hours) by English trawlers from each stock in each year. In the five north-east Atlantic stocks there has been a steady decline in catch-per-effort since 1946. This decline is primarily a function of stock size in relation to increasing fishing mortality, with short-term variations caused by fluctuations in recruitment and availability. For example, the Arcto-Norwegian cod stock shows three periods of temporary increase in catch-per-effort, due largely to the arrival of strong year-broods. The influence of such variable recruitment on catch and catch-per-effort is discussed in Sections 3 and 4.

The catch-per-effort data since 1955 for the north-west Atlantic cod stocks give a much more variable picture. The level of catch-per-effort is generally higher than for the north-east Atlantic stocks, and there is little evidence of a general decline in catch-per-effort with time.

(b) *Apparent fluctuations in abundance within years (seasonal availability)*

The annual value of catch-per-effort for a species is a index of the species' abundance in that year. Within eac year, every population has its particular pattern of avai ability, reflecting not a change in abundance but a regula change in the fish/fishing fleet relationship, which may b expected to influence the within-year distribution of effo throughout the north Atlantic; hence it must be made e plicit within the model. This variation in availability is ofte due to the movement of fish within a stock as a result o seasonal changes in the temperature or salinity regimes, o the distribution of the food organisms of the species. On of the most important changes in the distribution of fish i the annual migration of mature fish to the spawning ground At spawning time each year the fish congregate in a sma region of the stock area, and fishing fleets take advantag of the unusually high availability of the fish by concentratin their effort in this region.

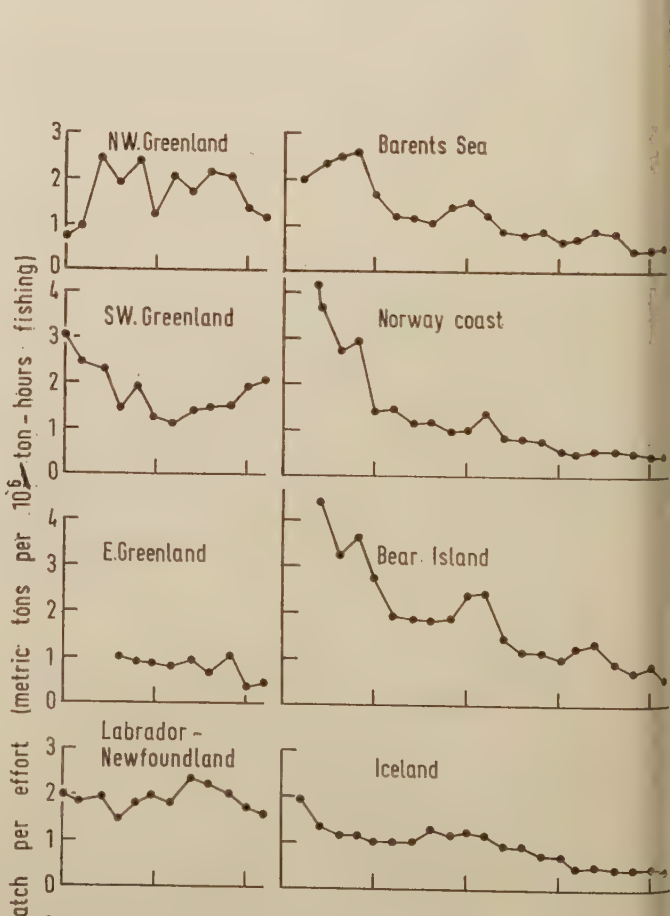
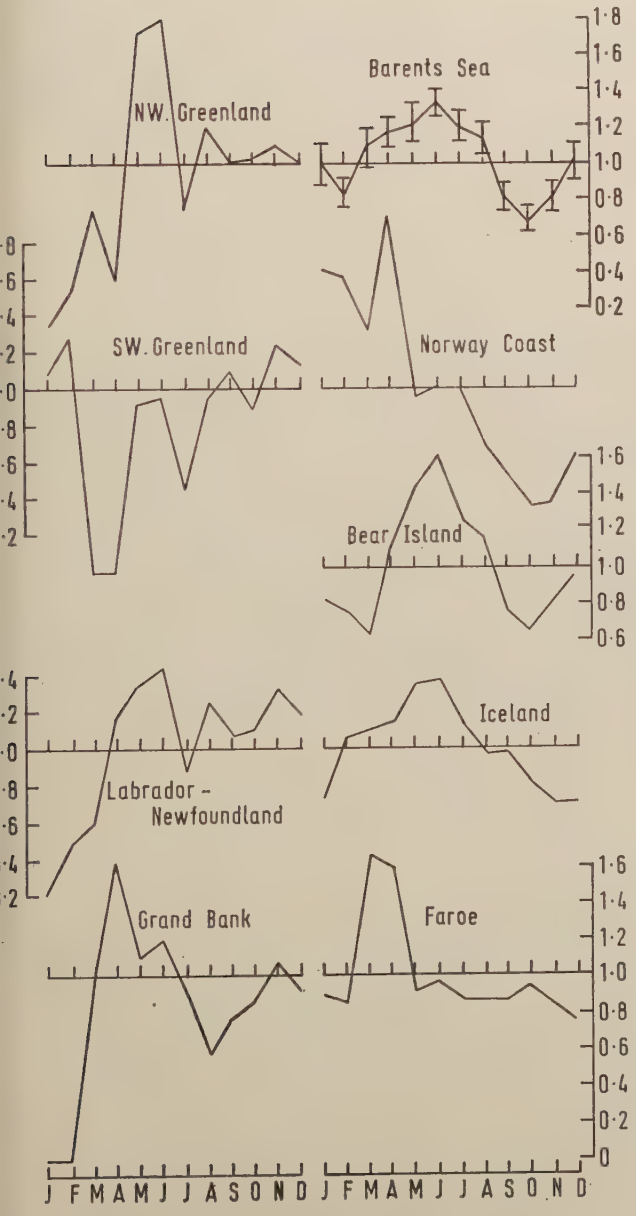


FIG. 9 Changes in catch-per-effort of English trawlers with time in 10 north Atlantic cod stocks.

produce an average monthly picture of variation in
-per-effort within each year, the monthly catch-per-
t values were expressed as percentages of the annual
. For the north-east Atlantic stocks English data of
per hundred hours' fishing were collated by months
the period 1946–66 (Faroe 1959–66), but in the north-
Atlantic only at south-west Greenland has the English
ng effort been sufficient to give a month by month pat-
of catch-per-effort. Lacking data in terms of the stan-
unit, the French 900–1800 t trawlers' catch and effort
have been used for north-west Greenland and Grand
k stocks, and Portuguese 900–1800 t trawlers' data have
used for the Labrador/Newfoundland stock. These per-
ages were then averaged over the number of years to
the monthly variation about the mean catch-per-effort
vn in Figure 10.

ne confidence limits were narrow, especially for the
h-east Atlantic stocks; as an example, the monthly pat-
of the Barents Sea is shown with one standard error



10 Monthly variation of catch-per-effort in 10 north
ntic stocks; for data used, see text.

about the mean. For the north-west Atlantic stocks, there were some months during the period December–May when no fishing occurred, principally due to ice conditions. These have been given zero catch-per-effort values, since no fishing was possible and the availability of the fish was thus nil.

The variation in monthly catch-per-effort in the different stocks forms two basic patterns in the north-east Atlantic. The more usual pattern is a symmetrical type, with a maximum in May to July and a minimum in October to February (e.g. Barents Sea and Bear Island). The other basic type is one with a spring maximum (March to May) and a gradual decline throughout summer and autumn (e.g. Norway coast, Faroe). Broadly speaking, these differences in pattern reflect the variation in the degree of aggregation of cod in different areas for spawning or feeding.

The north-west Atlantic stocks again give a more variable picture. North-west Greenland, Labrador/Newfoundland and Grand Bank all have maximum values in late spring or early summer (April to June) though the pattern is not symmetrical, January to March having lower values than August to November. South-west Greenland has a November to February maximum, and low values in spring and early summer. The variation due to month in the value of catch-per-effort is mostly within the range of annual mean ± 60 per cent.

In summary, it may be seen that the total catch of cod from the north Atlantic showed great increases from 1946 until the mid-1950s, when it reached a peak with the strong Arcto-Norwegian year-classes of that time. Since then (up to 1967), the total catch has decreased slowly but regularly, with an increasing proportion of the catch coming from the north-west Atlantic stocks, which now yield rather more than half of the total. The actual size of the catch taken from the north-east Atlantic, and the north-east Arctic in particular, has shown a steady decline, while the north-west Atlantic catch has increased rapidly. International fishing effort in the north Atlantic reached a peak in 1961, with an amount four times greater than the 1946 total but since 1961, it has fallen slightly and stabilized. Fishing effort in the north-west Atlantic, however, has continued to rise slowly, increasing its share of the total effort to about 30 per cent. This is mainly due to the development of mobile freezer trawlers, able to visit any stock likely to yield a good catch. Under the influence of these effort patterns, the abundance of all the north-east Atlantic stocks and some of the north-west Atlantic stocks has decreased regularly with time. The factors governing the relative effect of fishing effort on the different stocks are discussed in the following sections.

Biological Parameters of the orth Atlantic Cod Stocks

underlying relationship between the abundance of fish given stock and the amount of fishing effort applied to of great importance in stock management. Other factors es fishing effort must be involved in this relationship a theoretical structure defining the various population meters has been developed through the work of a num- of authors (Baranov 1918; Russell 1931; Ricker 1940, , 1948; Beverton and Holt 1957). Scientists have ap- ched the subject in different ways but the central tion is agreed. Depending upon the way in which fish elected to the fishery, the way in which they are subject ortality caused by fishing, and the magnitude of natural ality, for any given relationship of growth in weight age there exists an optimum age at which to catch the and a maximum possible yield that can be obtained the stock. (This statement disregards any possible effect shing on future recruitment by reducing the number of ning fish.)

his section is concerned with the quantification of these acteristics for the 10 north Atlantic cod stocks, so that vidual stock models may be drawn up which predict the t on a stock of variation in the amount of fishing taking e.

THE SIMPLE YIELD EQUATION

he yield model used in this exercise is largely of a Bever- and Holt type. These authors' equation was modified by sidering the abundance and weight of fish at discrete ages er than continuously with increasing length. The equa- giving the total yield from a year-class in its lifetime used, assuming that all fish recruit at the age of 1 year $t_1=1$ year). Therefore, the number of recuits each year, is the number of one-year-old fish in the stock at that e. It was assumed that selection took place over a variable nber of years, and was complete at a certain age in each k, this age being a characteristic of the stock. After com- e selection fish of all ages suffer the full fishing mortality, n the Beverton and Holt model. The resulting equation iven below:

$$Y=R\sum_{i=1}^{n}\frac{\varepsilon_i F}{(\varepsilon_i F+M)}\cdot(1-e^{-(\varepsilon_i F+M)})e^{-\sum_{J=1}^{i-1}(\varepsilon_j F+M)}w_i \qquad (3.1)$$

ere Y is the expected yield from a stock;
w_i is the weight of a fish of i years of age in the stock;
M is the natural mortality coefficient;
F is the fishing mortality coefficient, equal to qf, where q is the availability factor in the stock, and f is the fishing effort applied to the stock;
ε_i is the fractional effect of fishing effort on fish of i years of age in the stock;
R is the number of one-year-old fish present in the stock.
(The derivation of the yield equation is given in Appendix 5.)

This equation describes the yield obtained from any fish stock in a steady state. In the present context, it has a number of advantages over the standard Beverton and Holt equation:

(a) It is simpler to understand and compute, since it involves treating the numbers and weights of fish of discrete ages.
(b) It is possible to see, during the computation, which age-groups are supplying the bulk of the yield. In particular, when estimating the yield for a range of values of fishing mortality, it is possible to see not only the increased reliance on the younger age-groups under high levels of fishing mortality, but also the degree of increase of catch of each age with increasing fishing mortality. This may be important in the situation where potential spawners are caught before spawning, with an at present unknown effect on subsequent recruitment.
(c) Since, in some stocks, there appear to be considerable departures from the standard von Bertalanffy weight-at-age equation (e.g. in the Arcto-Norwegian stock), this model has the advantage of allowing the use of any theoretical or empirical weight-at-age relationships.
(d) The range of ages over which selection is allowed to occur (4 years for some stocks) gives a better approximation to the selection curves of the fishing gears in use than the *knife-edge* selection assumed in Beverton and Holt's yield model.
(e) Since ε_i is tabulated for all the important exploited ages, it would be possible, for example, to apply values of $\varepsilon_i > 1.00$ for older fish, if it were shown that they suffered more fishing mortality as a result of being concentrated upon by fishermen.

Thus, the model gives a degree of flexibility that may prove useful as the knowledge of fish and fisheries improves. ε_i may be changed for the partly-selected age-groups, if new mesh regulations arise, but less conveniently than Beverton and Holt's l_c may be changed. In this particular exercise, a period of 23 years has been chosen, during which time mesh sizes have increased from a non-regulated situation in 1946 to the present-day 130 mm minimum mesh size which is either in force or proposed for all of the stocks considered here save the stock at Faroe (110 mm). Estimates of ε_i have been derived from an average of these extremes.

3.2. ESTIMATION OF PARAMETERS

The yield equation chosen is a function of parameters connected with growth, natural mortality and fishing mortality, and recruitment. Each of these parameters must be estimated for each of the cod stocks in the north Atlantic. Once specified, an estimate of the expected yield for a given amount of fishing effort may be obtained.

3.2.1. *Growth*

When length is plotted against age the resulting curve is generally sigmoid, tending to an asymptote. Following Beverton and Holt's approach it is most convenient to

define growth using the von Bertalanffy curve which may be fitted by estimating the value of the three parameters in the equation $l_t = L_\infty (1 - e^{-K(t-t_0)})$, namely L_∞, K and t_0 (Gulland 1965). Figure 11 shows a typical growth curve fitted to data for north-west Greenland cod, and in Table 5 the predicted lengths at age are compared with recent observations (Horsted 1966). Table 6 gives the predicted values of length at age for all 10 stocks, together with the sources of the data used.

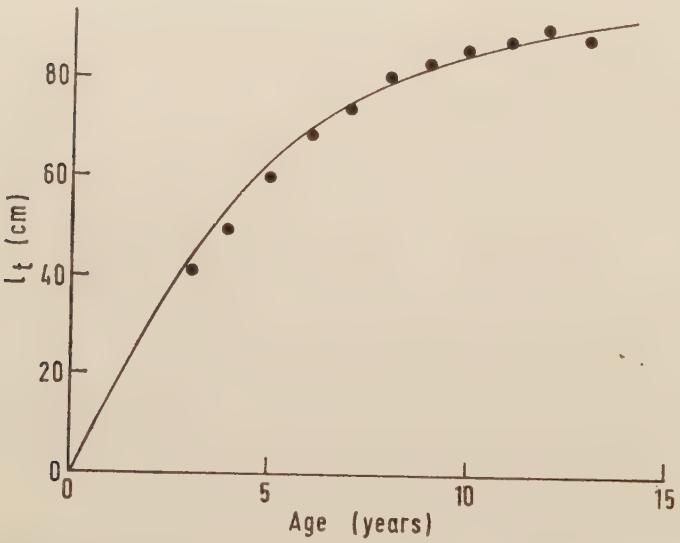


FIG. 11 Curve for predicting average length at age, based on data for north-west Greenland cod (1961–64).

TABLE 5 *Length at age (cm) of cod from north-west Greenland*

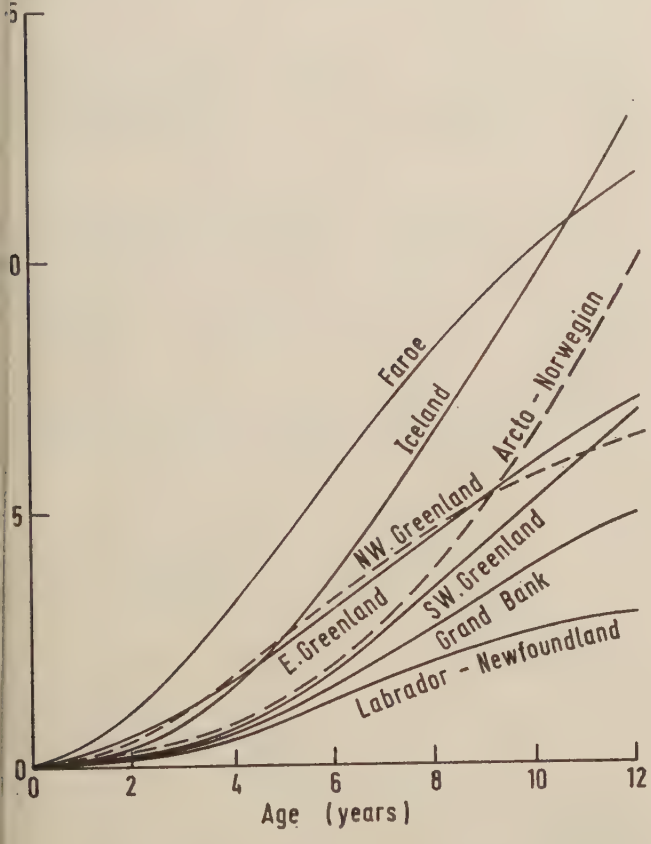
Age	Horsted (1966)	Predicted lengths from the calculated curve
	Data for 1960–65	Data for 1961–64
2	–	–
3	40	41
4	50	50
5	61	60
6	70	69
7	76	74
8	80	80
9	84	83
10	86	86
11	–	88
12	–	90

TABLE 6 *Predicted length at age (cm) in the different stocks*

Stock	Age (years)												Sources of data
	1	2	3	4	5	6	7	8	9	10	11	12	
Arcto-Norwegian*	22	31	38	46	52	61	71	78	82	91	98	105	Ponomarenko (1967)
Iceland	14	29	42	54	65	75	83	91	98	104	110	115	English data
Faroe	33	47	59	69	77	83	89	94	97	101	103	105	
North-west Greenland	15	31	45	55	63	70	75	79	83	85	87	89	ICNAF Sampling Yearbooks Vols 1–10
South-west Greenland	10	22	33	42	51	59	66	72	78	83	87	91	
East Greenland	27	38	47	56	63	70	75	80	84	88	91	94	
Labrador/Newfoundland	5	15	25	37	46	53	59	63	66	69	71	72	ICNAF Sampling Yearbooks Vols 1–10 and Fleming (1960)
Grand Bank	5	15	26	37	47	55	62	68	73	77	81	84	

* Barents Sea, Norway coast, Bear Island.

is also necessary to know the weight-length relationship ying to each stock, so that the weight at each age may alculated. The best fitting curves of the form $w=al^b$ ere w=weight (g) and l=length (cm)) were fitted to stock of cod; for example, for the north-west Green- cod (based on data for 1953–58 and 1965–66) a=0.011, 2.96. Figure 12 gives the resultant weight at age curves the 10 stocks. This shows that Faroe and Iceland cod the heaviest at any age in the north Atlantic, reaching ut 12 kg by the age of 12 years. Arcto-Norwegian cod a weight of about 10 kg at the same age, whereas cod the three Greenland stocks reach 6–7 kg in the same . The Labrador/Newfoundland and Grand Bank cod the smallest at age 12, reaching only 3 and 5 kg respec- ly by this time.



. 12 Weight at age curves for 10 north Atlantic cod stocks.

.2. *Mortality*

) *Natural mortality, fishing mortality and the availability coefficient*

Death may be due to either of two mutually exclusive tors—by fishing or by natural processes (i.e. all causes of ath other than fishing—e.g. death by starvation, preda- n, disease or senility). Although it is desirable to know of y changes in the magnitude of mortality with age it has t yet been possible to quantify any such variations in tural mortality. However, since in any fairly heavily ex- ited fish stock, such as those in the north Atlantic, it is nerally of a lesser magnitude than the mortality caused fishing, natural mortality has here been considered to be nstant with age. The basic equation is therefore

$$\left(\frac{dN}{dt_M}\right) = -MN_t \qquad (3.2)$$

ere N_t is the number of fish present at time t, and M is e natural mortality coefficient. Solving for N_t, we have: $=Ge^{-Mt}$, where G is a constant.

Mortality due to fishing has a magnitude dependent on the amount of fishing and the availability of fish. In the general case, for any part of the stock exposed to fishing, its effect may be expressed in a way analogous to (3.2) such that $N_t=G'e^{-Ft}$, where G′ is a constant. Since natural and fishing mortality are mutually exclusive,

$$N_t=G''e^{-(F+M)t} \qquad (3.3)$$

where G″ is a constant. Solving for G″, and when $t_1=(t_0+1)$ years, we have $N_{t_1}=N_{t_0}e^{-(F+M)}$, where N_{t_0} is the number of fish present at the beginning of the first year, N_{t_1} is the number of fish present at the end of that year, and (F+M)=Z the total mortality coefficient. From (3.3),

$$\log_e N_t=\log_e G''-(F+M)t \qquad (3.4)$$

or, using catch per unit effort as an index, c.p.e.$=qN_t$; then

$$\log_e(\text{c.p.e.})t=(\log_e G''+\log_e q)-(F+M)t. \qquad (3.5)$$

Plotting (3.5) the use of catch-per-unit-effort data alters only the intercept; the slope remains −(F+M)t, and when t=1 year the slope has the value −(F+M)= −Z. The plot of $\log_e$(c.p.e.) against age within a stock for a group of years gives a linear relation from which Z corresponding to the mean annual fishing effort over the period may be determined. A representative fit is shown for Iceland cod in Figure 13. The points corresponding to the youngest fish are not included in the regression because they are not fully selected to the fishery, and hence are not liable to the full mortality suffered by the older fish, as may be seen in the data in Table 7. Alternatively, total mortality may be estimated from the abundance of successive age-groups in consecutive years as $\log_e(\text{c.p.e.}_{t+1}/\text{c.p.e.}_{t_0})=-(F+M)$.

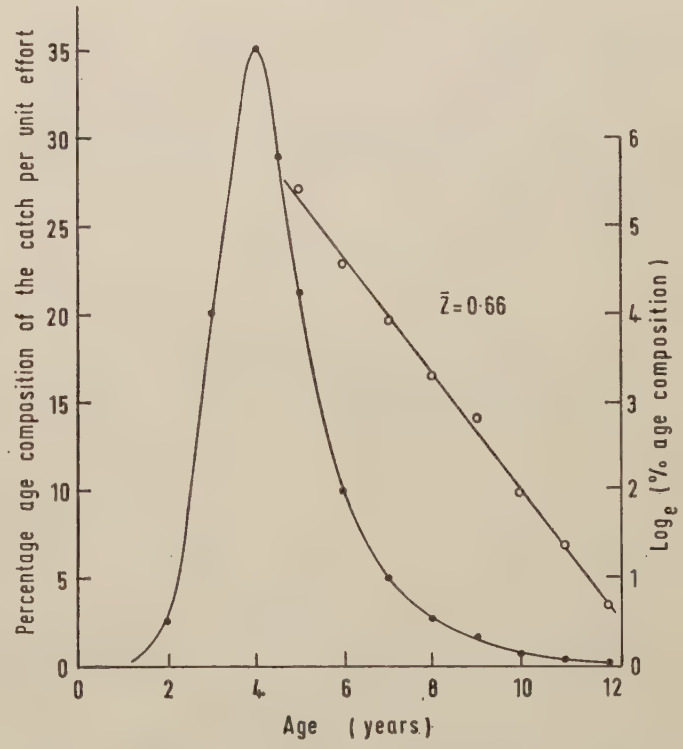


FIG. 13 Catch curve for Iceland cod (1955–64), from which the mean annual total mortality ($\bar{Z}$) has been calculated for the older fish.

TABLE 7 *Iceland cod: estimates of total mortality, Z, by age-groups and years*

Age	Year											$\bar{Z}$ (1955–6
	1955–56	1956–57	1957–58	1958–59	1959–60	1960–61	1961–62	1962–63	1963–64	1964–65	1965–66	
4– 5	−0.12	0.15	0.47	0.28	0.64	0.58	0.38	0.52	0.44	0.21	0.33	0.35
5– 6	0.37	0.74	0.78	0.79	1.18	1.10	0.51	0.72	0.79	0.85	0.69	0.77
6– 7	0.36	1.19	1.01	1.32	0.80	0.77	0.58	0.43	0.90	0.69	0.87	0.81
7– 8	0.89	0.73	0.57	1.15	1.18	0.47	0.83	0.90	0.86	0.66	0.91	0.83
8– 9	0.24	0.69	0.87	0.62	1.01	−0.31	0.08	0.73	0.89	0.56	1.23	0.60
9–10	2.30	0.96	1.29	0.64	1.51	0.55	0.99	0.80	1.95	0.90	0.90	1.16
10–11	−1.92	1.01	0.87	0.72	0.68	0.04	1.02	0.63	2.10	0.72	1.21	0.64
11–12	1.08	0.59	−0.15	0.62	−0.34	1.19	0.58	0.25	0.81	0.14	0.05	0.44
$\bar{Z}$ (5–12)	0.47	0.84	0.75	0.84	0.86	0.54	0.66	0.64	1.19	0.65	0.84	0.75

Having estimated the value of Z for a stock at a given time, it is necessary to estimate the relative sizes of F and M in Z=F+M. This may be done by calculating the linear regression of Z versus fishing effort (f) from the identity Z= qf+M, where the slope gives an estimate of q and the intercept on the y axis gives an estimate of M.

Appendix 6 gives the set of Z's and f's obtained for each stock, and Figure 14 gives the regression obtained for Barents Sea cod, from which q is estimated as 0.0014 and M as 0.29. Some of the north-west Atlantic stocks give poor estimates of q and a first approximation of the value of q may be obtained from $q=\frac{\bar{Z}-\hat{M}}{\bar{f}}$, where $\bar{Z}$ is the average total mortality coefficient during a period of years, $\bar{f}$ is the average level of fishing effort during that period, and $\hat{M}$ is an estimate of the natural mortality coefficient. $\bar{Z}$ and $\bar{f}$ are almost invariably known, and it is possible to get an idea of the size of q from this equation. As an example, it may be seen from Appendix 6 that the average value of Z at Barents Sea during the period 1946–66 was 0.86; the average level of fishing effort there in that period was 399 million ton-hours' fishing.

$$\bar{q}=\frac{\bar{Z}-\hat{M}}{\bar{f}}=\frac{0.86-\hat{M}}{399},$$

assuming $\hat{M}=0.10$, $\bar{q}=0.0019$ per 10^6 ton-hour fishing;

" $\hat{M}=0.30$, $\bar{q}=0.0014$ " " " " " .

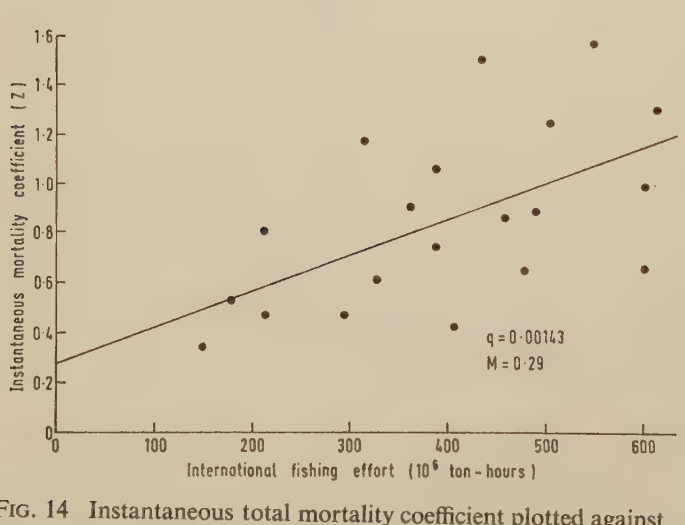


FIG. 14 Instantaneous total mortality coefficient plotted against international fishing effort, for Barents Sea cod.

These estimates of q are of the same magnitude as the esti mates already obtained (0.0014). Choosing an estimate of M midway between 0.10 and 0.30 gives an estimate of q 0.0016, which would serve as a first approximation.

Appendix 6 gives the values of Z, f, $\bar{Z}$ and $\bar{f}$ for all t stocks, and the estimates of q obtained for them. By com paring the values of q (Table 8) it may be seen that the three largest come from the three smallest stocks, and the fourt largest value comes from Bear Island—itself a small geogra phical area. The four smallest values are approximatel equal in magnitude, and refer to the Barents Sea, Iceland Labrador/Newfoundland and Grand Bank, the four larges stocks. The overall correlation of q and average catch i significant at the 90 per cent level.

TABLE 8 *The values of q for each stock and the average catch from each stock during the period 1955–66*

Stock	q (per 10^{10} ton-hours)	Average catch (1955–66) (10^3 metric tons)
Barents Sea	16	444
Norway coast	35	147
Bear Island	50	180
Iceland*	22	175
Faroe	75	28
North-west Greenland	25	262
South-west Greenland	100	65
East Greenland	150	20
Labrador/Newfoundland	17	269
Grand Bank	17	247

*N.B. The Iceland catch refers only to the immature fishery, and so underestimates the real size of the stock. $\bar{f}=0.75$

(b) *Selection to the fishery*

An important aspect of mortality is the degree of fishing mortality incident on partly selected fish. In the case of trawl gear or seine nets, once the fish have grown beyond a certain size they are considered fully selected by the gear, since if they enter the cod-end of a trawl, or are enclosed by the seine, they are unable to escape through the meshes. The percentage retention of fish by a trawl mesh of a certain diameter increases from 0 to 100 over a range of lengths (and thus ages) of fish. In this case, as a model of fishing mortality acting on fish of different ages, the period over which selection takes place (i.e. from ages A to B) may be defined such that:

fishing mortality is suffered up to age $t_A (0<t<t_A)$;
1 „ „ „ „ between t_A and $t_B (t_A<t<t_B)$;
1 „ „ „ „ after $t_B (t>t_B)$.

long the north Atlantic cod stocks, the age range over selection takes place is from 2 to 4 years' duration, ding largely on the growth characteristics of the parti- stock. A population of fast-growing individuals, such at of Faroe, has only two partly selected age-groups, as the slow-growing Labrador/Newfoundland popu- has four. The position of this selection range with re- to age is a function of size; for example, Faroe cod ully selected at 3 years of age although the Arcto- egian cod are not fully selected until 6 years old, but th stocks the fish have then reached approximately 2 kg ight. The position and range of this period may be fied by estimating values of ε_i, where ε_i is the frac- l effect of fishing effort on fish of i years old. For each during this period ε_i has a value between 0 and 1.00, value increasing with increasing i. Estimation of the s of ε_i is based on the catch in numbers of partly ted age-groups relative to the catch in numbers of fully ted age-groups. The theory was developed as follows.

T be the age at which fish first become liable to a full ng mortality; then $N_{T+1}=N_T e^{-(F+M)}$;

$_2 = N_{T+1} e^{-(F+M)} = N_T e^{-2(F+M)}$, etc., where F+ the total mortality coefficient acting upon fully selected The catch in numbers of fish of age T=

$$\int_0^1 F N_T e^{-(F+M)T} dt = \frac{F}{F+M} N_T (1-e^{-(F+M)}). \quad (3.6)$$

catch in numbers of fish of age T − 1=

$$\frac{\varepsilon_{T-1}F}{\varepsilon_{T-1}(F+M)} \; N_{T-1} \; (1-e^{-(\varepsilon_{T-1}F+M)}).$$

$N_T=N_{T-1}e^{-(\varepsilon_{T-1}F+M)}$. Therefore, the catch in ber of fish of age T/the catch in numbers of fish of age 1=

$$\frac{\varepsilon_{T-1}F+M)}{\varepsilon_{T-1})(F+M)} \cdot e^{-(\varepsilon_{T-1}F+M)} \cdot \frac{(1-e^{-(F+M)})}{(1-e^{-(\varepsilon_{T-1}F+M)})} \cdot \quad (3.7)$$

ilarly, again using the catch in numbers of fish of age T reference, it may be shown that the catch in numbers of of age T/the catch in numbers of fish of age T − 2=

$$\frac{(\varepsilon_{T-2}F+M)}{(\varepsilon_{T-2})(F+M)} \cdot e^{-(\varepsilon_{T-2}F+M)} e^{-(\varepsilon_{T-1}F+M)} \cdot \frac{(1-e^{-(F+M)})}{(1-e^{-(\varepsilon_{T-2}F+M)})} \cdot \quad (3.8)$$

Equations (3.7) and (3.8) are sufficient to evaluate ε_{T-1} and ε_{T-2} for stocks with a 2-year selection range. Third and fourth equations may be derived for those with a 4-year range, such as the Labrador/Newfoundland stock. Knowing the percentage age-composition of the catches, and the age T at which selection becomes complete, we may calculate the values of C_T/C_{T-1}, C_T/C_{T-2}, C_T/C_{T-3}, etc. Provided that the value of F+M is known, and M may be estimated, the equations above are implicit in ε_{T-1} and ε_{T-2}. The equations are not independent and must be solved in the order given, since the second (3.8) requires the use of the estimate of ε_{T-1} obtained from the first (3.7). The solutions were carried out by hand for a range of values of M (0.1–0.3). The values of C_T/C_{T-j} (where j=1 to 4) used in the equations were obtained by averaging the annual values over the period 1946–66.

Figure 15 (page 20) shows the trends in ε with age in the 10 stocks. Faroe and Iceland cod may be seen to enter the selection range earliest, becoming fully selected at ages of 3 and 5 respectively. Cod from most of the other stocks become fully selected at 6 or 7, with the exception of east Greenland (8) and Norway coast (10). Cod are caught at the Norway coast when they congregate for spawning, and only the older, mature cod are present to be caught—hence the special position of the Norway coast selection pattern.

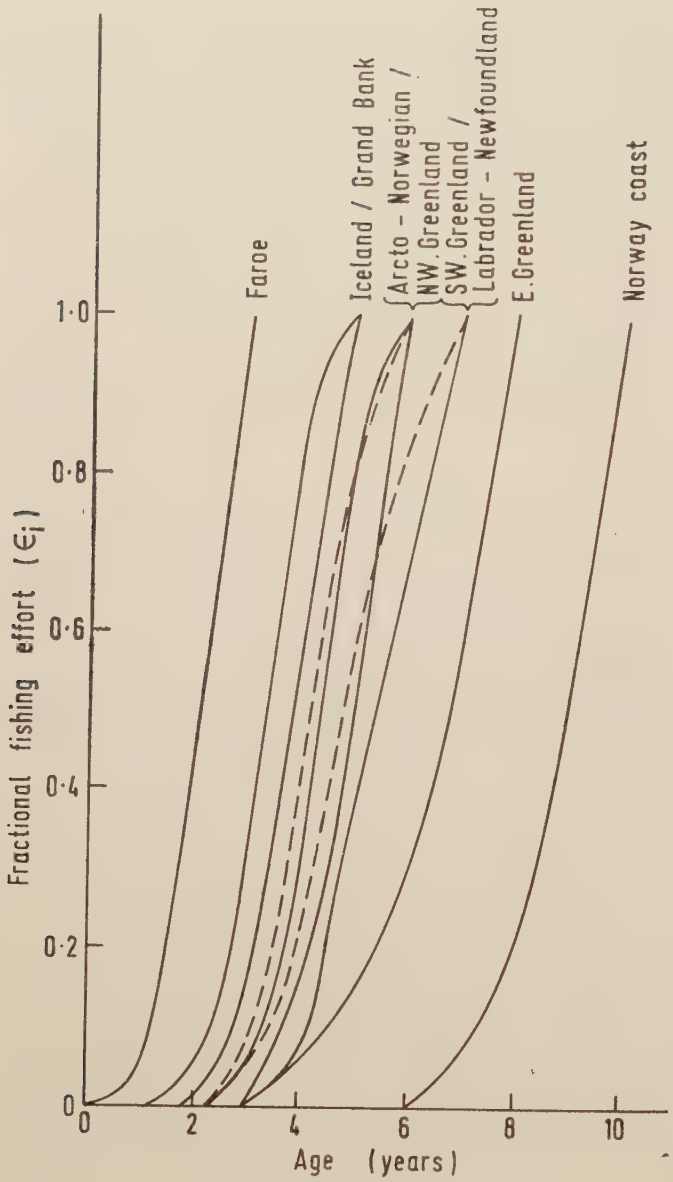


FIG. 15 The fractional fishing effort on the north Atlantic cod stocks.

3.2.3. *Recruitment*

The estimation of the number of one-year-old recruits to each stock may be done by extrapolating backwards the data on the catch in numbers of fully selected fish. Assuming steady-state conditions, or a year-class situation, the number of one-year-old cod in the population, R, suffer either partial (in the case of Faroe) or zero fractional fishing mortality, as well as the constant level of natural mortality. With increasing age, the cod suffer increasing total mortality, until it reaches a constant value after the fish have become fully selected.

Let the number of one-year-old cod, $N_1 = R$.
Therefore,

$$\text{number of two-year-old cod alive} = Re^{-(\epsilon_1 F + M)},$$

$$\text{and number of i-year-old cod alive} = N_i = Re^{-\sum_{j=1}^{i-t} (\epsilon_j F + M}$$

The catch, in numbers, of i-year-old cod,

$$C_i = \frac{\epsilon_i . F}{\epsilon_i . F + M} N_i (1 - e^{-(\epsilon_i . F + M)}).$$

If $i \geqslant T$, the age at full selection, $\epsilon_i = 1.00$

$$\text{and } C_i = \frac{F}{F+M} N_i (1 - e^{-(F+M)}). \quad (3.9$$

Therefore,

$$C_i = \frac{F}{F+M} . Re^{-\sum_{j=1}^{i-1} (\epsilon_j . F + M)} (1 - e^{-(F+M)}). \quad (3.10$$

Therefore,

$$R = C_i . \frac{F+M}{F} . \frac{e^{+\sum_{j=1}^{i-1} (\epsilon_j . F + M)}}{(1 - e^{-(F+M)})}. \quad (3.11$$

When $i = T$,

$$R = C_T \frac{F+M}{F} . \frac{e^{+\sum_{j=1}^{T-1} (\epsilon_j . F + M)}}{(1 - e^{-(F+M)})}. \quad (3.12)$$

Therefore, for any year-class, an estimate of the number of one-year-old recruits may be obtained if the following are known:

(1) the catch in numbers of just fully selected cod;
(2) the total mortality suffered by fully selected members of the year-class;
(3) an estimate of the natural mortality coefficient;
(4) the values of ϵ_i for fish of ages $0 < i < T - 1$.

Table 9 gives estimates of average recruitment ($\bar{R}$) over a specified period obtained in this way from each of the 10 cod stocks; as might be expected, the values are approximately in proportion to the size of the stocks. (Correlation is significant at the 95 per cent level.)

TABLE 9 *Estimation of the number of recruits to each stock*

Stock	Time period to which data refer	$\bar{Z}$	$\bar{F}$	Age at full selection, T (years)	$(\Sigma \varepsilon j)\bar{F}+(T-1)\bar{M}$	(1) $\frac{1}{1-e^{-(\bar{F}+\bar{M})}}$	(2) $\frac{\bar{F}+\bar{M}}{\bar{F}}$	(3) $e^{[(\Sigma \varepsilon j)\bar{F}+(T-1)\bar{M}]}$	(4) Catch (nos $\times 10^{-6}$) of fish of T years of age	R=columns 1 × 2×3×4 ($\times 10^{-6}$)	$R=\frac{\bar{Y}}{\bar{Y}/R}$ ($\times 10^{-6}$)
Barents Sea	1946–66	0.86	0.66	6	1.73	1.733	1.303	5.641	44.332	565	655
Norway coast				10							
Bear Island	1946–66	1.17	0.97	6	1.68	1.449	1.206	5.366	15.952	150	240
Iceland	1955–66	0.75	0.55	5	1.45	1.894	1.364	4.259	18.510	210	170
Faroe	1959–66	0.80	0.60	3	0.70	1.815	1.333	2.014	3.321	16	21
North-west Greenland	1956–65	0.57	0.37	6	1.50	2.304	1.541	4.482	18.473	294	275
South-west Greenland	1956–65	0.56	0.36	8	2.01	2.331	1.556	7.463	3.685	100	100
East Greenland	1956–65	0.58	0.38	9	2.08	2.273	1.527	8.005	0.810	23	22
Labrador/Newfoundland	1955–65	0.45	0.25	8	1.81	2.762	1.800	6.110	22.073	671	730
Grand Bank	1959–66	0.51	0.31	6	1.40	2.506	1.645	4.055	29.907	500	600

An alternative estimate of average recruitment ($\bar{R}$) may be obtained using the yield equation (3.1). Yield per recruit may be estimated from the parameters for growth, natural mortality and fishing mortality; then

$$\bar{R}=\frac{\text{Average actual yield}}{\text{Average predicted yield per recruit, } \bar{Y}/R}=\frac{\bar{Y}}{\bar{Y}/R}.$$

For example, in the Barents Sea the average predicted yield per recruit during the period 1946–66 was 0.62 kg (assuming q=0.0016), and the average yield was 407 000 tons, giving the estimate $\bar{R}=407/0.62=655\times10^6$ one-year-olds. The final column of Table 9 contains the estimates of $\bar{R}$ obtained in this way for the various stocks, and these values are used in the remainder of this paper.

3.3. YIELD-PER-RECRUIT RELATIONSHIPS IN THE NORTH ATLANTIC COD STOCKS

The computations described in Section 3.2.3. may also be used to define the curves of yield per recruit against fishing mortality shown in Figure 16. It may be seen that Faroe gives the highest values of yield per recruit, with a maximum of approximately 1.3 kg; this is the weight of a Faroes cod of between 2 and 3 years of age. Thus, to obtain a yield per recruit of 1.3 kg for Faroe cod is the equivalent of removing all the cod from the stock when they reach 2 to 3 years of age.

The stocks at Iceland, north-west and east Greenland have a maximum yield per recruit of approximately 1.0 kg, followed by the Arcto-Norwegian and south-west Greenland stocks at about 0.6 kg, and the Labrador/Newfoundland and Grand Bank stocks with approximately 0.4 kg. In all these stocks the maximum yield per recruit corresponds to the weight of a fish at an age of 3–4 years.

The curves are illustrated to show the comparison between stocks and also to show, by comparison of Figure 16 with Figure 12, that the magnitude of the yield per recruit is largely a function of weight at age. In fact, the curves shown for the Arcto-Norwegian and Icelandic stocks both exclude here the influence of yield in the respective spawning fisheries, so that neither will correspond exactly to other assessments of yield per recruit in the total fisheries.

The yield-per-recruit axis of Figure 16 may be effectively converted to a yield axis by multiplying by the estimated average number of recruits and altering the scale. For example, a yield-per-recruit value of 0.9 kg per recruit, with an estimate of 50 million one-year-old recruits, becomes a yield of $45\times10^3\times10^6$ g, i.e. 45 000 metric tons. The fishing mortality axis may be similarly converted to a fishing effort axis by dividing by the availability, q, from the equation F=qf. Thus, a fishing mortality of 0.5 with a q of 0.002 per 10^6 ton-hours gives a fishing effort of 250×10^6 ton-hours' fishing.

In this way, although the form of the equation remains the same, the axes are altered to a more useful form, because the new plot gives a predicted yield for a certain amount of fishing effort. Superimposed on the theoretical curve, a scatter diagram of the actual yield for known annual amounts of effort may be produced. The scatter about the curves is very wide in most cases, principally due to varia-

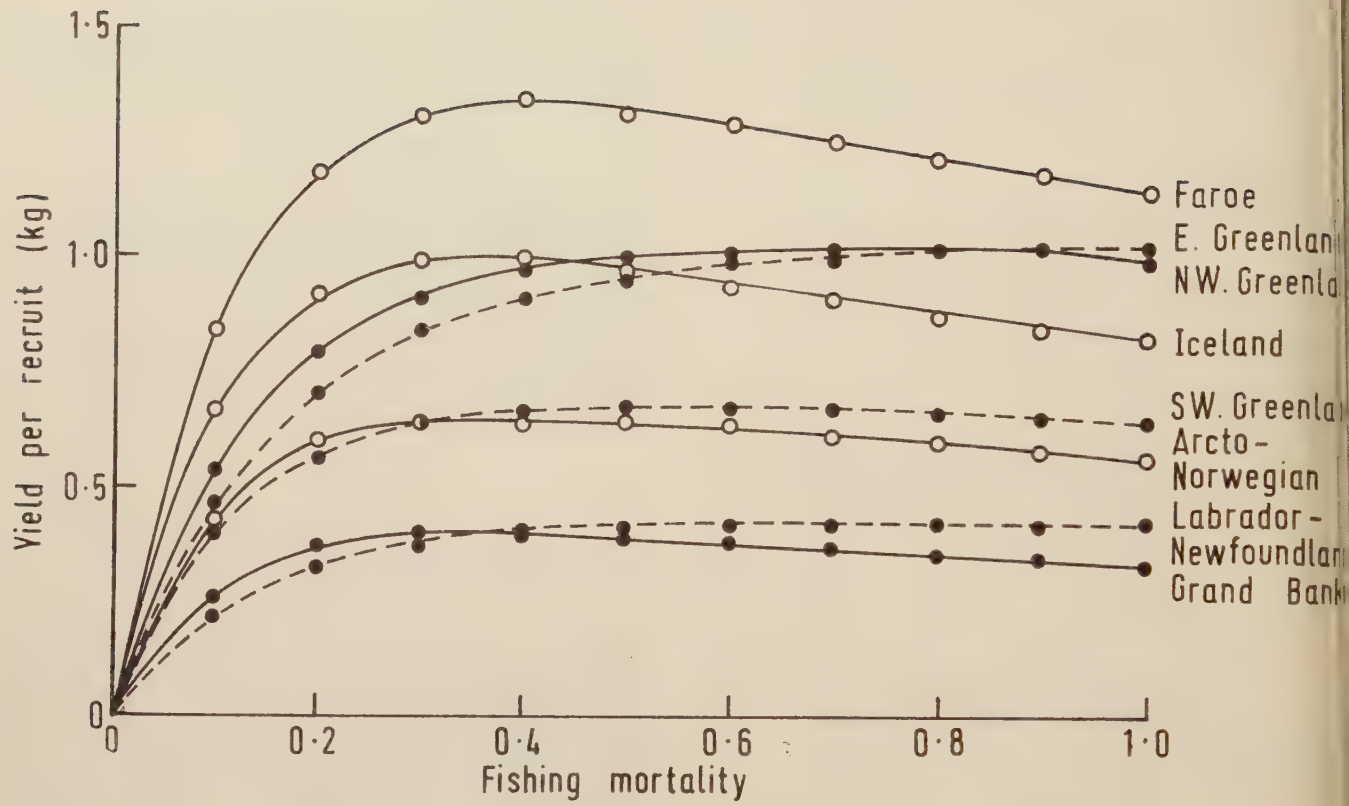


FIG. 16 Yield per recruit curves for the north Atlantic cod stocks.

tions in recruitment from year to year, but partly due to variation in availability, especially in the north-west Atlantic. In the example of the Barents Sea given in Figure 17, the yield in two years, 1955 and 1956, was around 800 000 tons—approximately double that predicted by the equation. This may be shown to be due to very strong year-classes being present. Conversely, in 1964 and 1965, very weak year-classes resulted in a total yield of about 200 000 tons, approximately half that predicted by the equation.

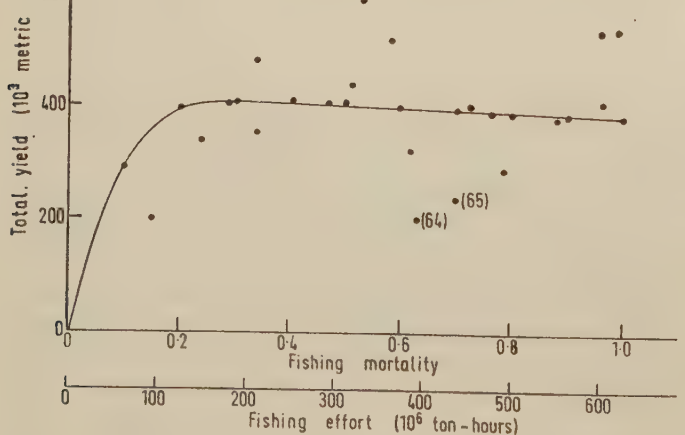


FIG. 17 Total yield of Barents Sea cod plotted against fishing effort.

A knowledge of the amount of fishing effort giving the maximum yield per recruit (and thus maximum yield under the assumed conditions of constant recruitment) is of great use in the management of separate stocks. In the case of many of the north Atlantic stocks there is a whole range o values of fishing effort which should give a yield close to th maximum. Taking a direct approach to the economics o fishing, the lowest level of fishing effort that gives the maxi mum yield could be defined as one optimum level of effor depending upon the criteria for judgement.

The values of maximum yield per recruit, optimum fishin effort and theoretical maximum yield (again assuming con stant recruitment at the levels of Table 9) are given in Tabl 10, together with the 1966 values of observed fishing effor and yield. This table shows that the level of fishing effort i the north Atlantic in 1966 was only slightly (5 per cent above that of the optimum level defined above, but that th distribution of fishing effort was unbalanced. Comparin the optimum and actual fishing efforts, the north-east Atlan tic stocks all seem overexploited, and the north-west Atlanti stocks all seem underexploited (with the notable exceptio of the Grand Bank stock). It is true that the values of q use for the north-west Atlantic stocks are uncertain, but never theless it seems clear that, on biological grounds, mor emphasis should be placed on fishing the north-west Atlanti grounds, rather than the already overexploited north-eas Atlantic grounds. The Norway coast fishery is omitted fro Table 10 because of the difficulties of establishing a meanin ful yield curve.

The total yield in 1966 from all these stocks in the nort Atlantic (1594×10^3 m tons) is 93 per cent of the maximu sustainable total yield. With the exception of north-wes Greenland, Labrador/Newfoundland and Grand Bank, eac had a total yield of less than the theoretical maximum though of course in any particular year this performance i biassed by the relative abundance of recent year-classes.

LE 10 *Comparison between the theoretical values of maximum yield per recruit, optimum fishing effort and maximum yield and those observed in 1966*

	Theoretical values			1966 values		
	Maximum Y /R	Optimum effort (10^8 ton-hours' fishing)	Maximum yield (10^3 metric tons round fresh)	Actual effort (10^8 ton-hours' fishing)	Actual yield (10^3 metric tons round fresh)	% of theoretical maximum yield
hts Sea	0.57	3.10	422	4.90	289	68
Island	0.59	1.00	174	1.49	55	32
nd	1.00	2.10	170	2.85	133	78
e	1.33	0.55	32	0.68	23	72
h-west Greenland	1.00	2.40	280	1.88	305	109
n-west Greenland	0.67	0.50	72	0.32	61	85
Greenland	1.02	0.70	23	0.28	13	57
ador/Newfoundland	0.41	4.10	297	2.41	428	144
d Bank	0.40	1.80	250	2.23	287	115
l, North Atlantic		16.25	1720	17.04	1594	93

The Construction of a Dynamic Model North Atlantic Cod Stocks

THE BIOLOGICAL AND NON-BIOLOGICAL FACTORS INFLUENCING THE DISTRIBUTION OF INTERNATIONAL FISHING EFFORT

ıe previous section, estimates of the important popula- parameters were obtained for each of the 10 stocks. The es of these parameters, inserted in the yield equation, : yields from the different stocks as a function of fishing rt. Satisfactory correlations between expected yields and al yields were obtained in most cases, and those stocks ng non-significant correlations had expected yields and ıal yields of the same order of magnitude.

)eviations from the static, steady-state, yield equation are ɔe expected, chiefly because of variations in recruitment n year to year. Furthermore, annual values of predicted d for a given amount of effort are not truly independent each other, as is assumed in a least-squares statistical nique, because the recruitment of an especially strong weak) year-class will have affected the actual yield ob- ıed for a given amount of effort, over a number of years. e steady-state yield equation, averaged as it is over a long iod of time, and incorporating a number of year-classes varying strength, gives a line which is driven through the ldle of these points and so obscures important informa- n on the variation of the stock with time. This limitation can be overcome by incorporating the *individual-stock* models into a time-varied *north Atlantic cod stocks* model.

The level of standardized fishing effort by each nation on each of the 10 north Atlantic cod stocks is known over a period of years (Appendix 3). These fishing efforts may be combined by nations and treated as the independent variable, X, in a combined yield model with 10 possible dependent variables, $Y_1, Y_2 \ldots . Y_{10}$, giving the predicted yield from each of the 10 stocks. Consequently, the basic intention of the model is that it should redistribute the known north Atlantic fishing effort of each nation between the different stocks on the basis of the yield expected from each, the criterion of accuracy of the model being that the predicted pattern of effort will closely parallel the known pattern of effort.

The *deterministic* yield-per-recruit model defines the variation in yield at different levels of fishing mortality, based on the parameters of availability (q), growth and natural mortality in each stock, but in order to allow for the great variability of the data, the model must be flexible enough to be extended to include additional variables. It is clear, for instance, that to get a simulation of a closer degree than that obtained with the simple yield models, it is necessary to allow recruitment to vary from year to year about the average values estimated in Section 3. For these recruitment

BLE 11 *Variation in recruitment of north Atlantic cod, in percentage of long-term mean as one-year-olds in calendar years*

Calendar year	Stock					
	Arcto-Norwegian*	Iceland	Faroe	North-west and south-west Greenland	Labrador/ Newfoundland	Grand Bank
1946	81	30	100			
47	81	30	100			
48	111	38	100			
49	172	39	100			
1950	189	150	100			
51	260	132	100			
52	110	80	100			
53	52	61	100			
54	76	88	43			
1955	126	55	114	45	132	185
56	83	79	29	45	132	185
57	108	143	86	73	154	111
58	122	61	100	146	82	111
59	145	100	71	70	66	111
1960	115	46	71	70	110	50
61	58	46	100	108	121	74
62	30	52	86	140	143	50
63	68	71	114	70	121	55
64	232	61	43	70	121	133
1965	176	143	114	70	132	377
66	113	100	129	93	66	144
67	112	100	100	100	100	100
68	112	100	100	100	100	100
69	112	100	100	100	100	100
1970	122	100	100	100	100	100
71	100	100	100	100	100	100
72	100	100	100	100	100	100
73	100	100	100	100	100	100
74	100	100	100	100	100	100
1975	100	100	100	100	100	100

Barents Sea and Bear Island.

estimates to be realistic in a dynamic situation, an age-composition of each stock must be introduced in the first year of the simulation (1946), and up-dated each year by the requisite number of one-year-old recruits. The action of fishing on each stock then removes a certain number of fish of different ages, which are replaced, or not, depending on whether the stock is decreasing or increasing in number, by the ageing of younger fish at the end of each year. In this way, the varying strengths of year-classes, so obvious in many of the north Atlantic cod stocks, is revealed in the age-compositions of both the stocks and the international catch. Estimates of year-class strengths, obtained by back-calculating the catches of cod from the different year-classes, are available for all the north Atlantic stocks except east Greenland (Garrod, pers. comm.), and are given in Table 11.

It is also clear that each stock has a fairly rigid seasonal pattern of availability, as described in Section 2, which is removed by averaging over the year when treating each stock separately, but which must be taken into account when dealing with the complex interactions that determine the monthly distribution of fishing over a number of stocks. The skipper's individual experience, based on many years' fishing of each ground in all seasons, has given him a good knowledge of the seasonal fishing pattern characteristic of each; this pattern of availability must enter into his choice of the best ground.

In addition to annual biological fluctuations in the stock, and within-year seasonal variations, there are also economic considerations which enter into the choice of fishing ground and determine the distribution of fishing effort, and hence catch. This is an area of extreme complexity but initially allowance has been made for three important components of the variable; these are distance from port, the availability of other commercially-valuable species on the same ground, and the value of catches from the stock in question.

The majority of vessels participating in the north Atlantic cod fishery over the period considered have stored their catch on ice. On these vessels a point is reached where the increased value of catches taken by continued fishing is balanced by the deterioration of fish already caught. This, in conjunction with design characteristics for fuel and fish storage, has resulted in trips of fairly fixed duration in English distant-water side trawlers—usually about 3 weeks. In these circumstances closer fishing grounds allow a higher proportion of fishing time and may attract a high proportion of fishing effort, even though the catch-per-unit-effort may be lower than on more distant grounds. In recent years this constraint has to some extent been overcome by the development of trawlers which freeze their catch at sea and whose trip duration is limited by characteristics other than the keeping quality of the product. This aspect of mobility would have to be incorporated in further extensions of the model.

Table 12 gives the data required to estimate the distance weighting factors for the different stocks with respect to the English fleet. The first column shows that the average length of a trip by a 500–900 t wet-fish side trawler during the period 1946–67 increases with the distance of the ground from the home port. This is because the larger fishing vessels tend to fish the more distant stocks. The shortest trips are of 2–2½ weeks' duration, and are to Faroe and Iceland. Trips to most of the other stocks are of about 3 weeks' duration giving an average of 130 hours' fishing and a trip fishing effort capacity of approximately 80 000 ton-hours. The larger freezer and factory trawlers are able to stay out much longer than wet-fish side trawlers, with average trip lengths of 7 weeks and 18 weeks respectively in 1967. During this time, they may visit several stocks.

The fifth column in Table 12 gives the number of hours' fishing per day absent (D.A.) at each stock. For the wet-fish side trawlers of 500–900 t there is a maximum for Faroe and Iceland at 7½–8 hours/D.A., while the Arcto-Norwegian stocks and east Greenland have values of 6½–7 hours/D.A. The Grand Bank stocks have a value of 6–6½ because of the rather long distance involved, while north-west and south-west Greenland and Labrador give values of around 4 hours/D.A. The figures for the larger freezer and factory ships

TABLE 12 *An estimation of economic weighting factors for the English fishing fleet*

Region	Days absent per trip	Hours' fishing per trip	Average tonnage of otter-trawlers	Ton-hours' fishing per trip	Hours' fishing per day's absence	Factors (for details, see text)			Overall factor (1×2×3)
						(1) Distance	(2) Species	(3) Value	
						Hours' fishing (% w.r.t. Faroes)	Weighting factor for species other than cod	Quality (% w.r.t. Faroes)	
500–900 ton trawlers									
Barents Sea	21.8	145.4	600	87 240	6.67	81	126	89	91
Norway coast	20.7	130.0	600	78 000	6.28	76	136	85	88
Bear Island	20.0	140.0	600	84 000	7.00	85	114	78	76
Iceland	18.5	138.5	500	69 250	7.49	91	133	96	116
Faroe	15.0	123.8	300	37 140	8.25	100	152	100	152
North-west and south-west Greenland	22.8	99.4	750	74 550	4.36	53	106 119	79	44 50
East Greenland	19.3	128.6	750	96 450	6.66	81	163	95	126
Labrador/Newfoundland	23.0	91.8	750	68 850	3.99	48	115	80	44
Grand Bank	25.2	156.9	750	117 700	6.23	76	120	90	82
900–1800 ton trawlers									
Barents Sea Norway coast Bear Island	46.0	514.8			11.19				
North-west Greenland Labrador	51.4	474.3			9.23				
1800+ ton trawlers									
Grand Bank	126	1413			11.20				

the advantage in increased hours' fishing per D.A. to ined by prolonging a trip.

pressing the values as percentages with respect to the e value gives the magnitude of the weighting factors o distance (factor 1). The second non-biological factor dered here to influence the distribution of fishing effort expected abundance of other commercially important species in the catch. Table 13 gives the average percentage of haddock, redfish and saithe in the catches compared with cod, and the resulting percentage by weight by which the catch of cod should be raised so as to represent the whole catch. It is noticeable that east Greenland with its redfish and Faroe with its haddock have high values of this weighting factor, all of which appear in Table 12 (factor 2).

LE 13 *Percentage composition by weight in the catch from various stocks; cod and other important species (see Table 5)*

	Column A	Column B	B/(A+B)	Major alternative species
	Cod	Haddock, redfish, saithe	%	
n-east Atlantic stocks: data averaged for 1947–66				
nts Sea	57.7	20.1	25.8	Haddock
way coast	24.3	13.9	36.4	Saithe
Island	80.0	12.5	13.5	Redfish
nd	43.5	21.5	33.1	Haddock/saithe/redfish
h-west Atlantic stocks: data averaged for 1955–66				
e	35.6	39.1	52.4	Haddock
h-west Greenland	88.2	6.0	6.4	Redfish
h-west Greenland	81.6	15.3	15.8	,,
Greenland	31.8	53.0	62.5	,,
ador/Newfoundland	82.2	14.0	14.6	,,
nd Bank	69.8	17.9	20.4	Haddock/redfish

ata on the third weighting factor, the value of the catch n the different areas, are taken from UK landing figures he MAFF Sea Fisheries Statistical Tables. These give the ght (10^3 cwt) and value (£10^3) of the demersal wet-fish dings by English trawlers from the different grounds. The ue of the catch has varied between £2 and £4 per cwt r the period considered, depending on the quality of the . In general, for non-freezer fishing vessels, the more ant the fishing ground the poorer is the condition of the when it is landed in England, and the lower the price t is received. It is also true that cod from different unds have different characteristics; for example, cod m Bear Island tend to be younger than cod from the rents Sea, and thus bring lower prices. There has been a nd in value per unit weight with time but the relative ue of fish from different grounds within years has re-ined fairly stable. The relevant data from the above-ntioned tables for the years 1955, 1961 and 1966 are given Table 14, expressed as a percentage of the value of the cod ded from Faroe. This table shows that cod from Faroe d Iceland, the two stocks closest to the English fishing rts, have the highest values. Bear Island cod, being mainly all cod (codling), have the lowest value. Cod from the rth-west Atlantic have relatively high values due to the gh percentage of freezer trawlers fishing there. The figures the final column of this table also appear in Table 12 as tor 3, under the heading 'value'.

The last column of Table 12 gives the product of the three tors. This shows the weighting in favour of Faroe and eland (and east Greenland, principally because of the pre-nce of redfish), and against north-west and south-west reenland and Labrador. The Grand Bank stock is given a nilar weighting factor to the Arcto-Norwegian stocks, cause of the greater trip lengths associated with the more stant north-west areas.

TABLE 14 *Value of cod landed (% of the value for Faroe)*

Stock	1955	1961	1966	Average
Barents Sea	90	88	89	89
Norway coast	81	90	84	85
Bear Island	78	73	84	78
Iceland	92	98	97	96
Faroe	100	100	100	100
NW./SW. Greenland	86	79	71	79
E. Greenland	–	85	105	95
Labrador/Newfoundland	–	73	87	80
Grand Bank	109	82	79	90

This product weighting factor is not applied to all of the nations equally. The values of the factors were calculated largely on the basis of English data, and so apply strictly only to the English fishing fleet. The second factor, that due to the presence of other species in the catch, is applied to all nations equally, since it is a stock characteristic. Germany and Scotland also have both the quality and distance factors applied to their fishing effort, since their fishing fleets show great similarities to the English fleet and are based close to each other. Russia and Norway however fish mainly in the north-east Arctic, and for them the distance factors applied to these stocks are removed, since their fleets are based in the area; the value and distance factors are retained for the north-west Atlantic stocks. The Faroese have the value factor applied to their fishing effort, but the distance factors for the north-east Atlantic stocks are removed, although they are retained for the north-west Atlantic stocks. France, Portugal and Spain, fishing mainly the north-west Atlantic stocks, include all except the value factor.

It is self-evident that these weighting factors could be further refined but this present approach has been adopted to find out whether the somewhat crude assumptions involved are critical to the simulation as a whole. Thus, in addition to the parameters of the deterministic model, this time-varied model also incorporates variations in recruitment between years and stocks, seasonal variations in availability, and a product weighting factor taking into account some of the non-biological factors influencing the distribution of fishing.

4.2. THE MODEL

The requirement of the model is that the national fishing effort should be distributed on a monthly basis, in proportion to the relative abundance of the 10 stocks, to re-create the observed distributions of annual catch and fishing effort on each stock over the period 1946–68. The parameters determining individual stock size in relation to fishing effort, and other factors influencing the distribution of effort, have been described. The method of allocation of each nation's monthly fishing effort on the basis of these parameters is as follows.

The amount of fishing effort in one trip by each country is applied speculatively to each stock in turn. The value of the fishing mortality generated by that effort will be dependent on the month in which it is applied but will give a catch that is characteristic of the product of the density and the availability of each stock at that time. The catch obtained from each stock is then converted to an economic variable, using the appropriate economic weighting factors, and the fishing effort of that nation is then divided between the stocks on the basis of proportionality with the economic variable.

Using the above procedure for distributing the available national fishing effort between the stocks, the effect of that fishing effort on each of the stocks and the number of survivors left in each stock may then be calculated through successive months of a year. The sum of catch and fishing effort by each country and for each stock is collated annually and every year the number of new recruits is added to the population to represent the recruiting year-class, and the computation is continued.

The data required for the working of the computer model are as follows:

(1) the initial size of each population in 1946—in terms of the numbers of fish of each age (array AA);
(2) the annual number of one-year-old fish entering each population as a result of the previous year's spawning (array AB);
(3) the amount of fishing carried out by each nation in the north Atlantic in each year since 1946 (array AC);
(4) the amount of fishing effort involved in a single trip to any north Atlantic stock by each nation (array AD);
(5) the values given to each stock's parameters, as estimated in Section 3, i.e. weight at age, degree of selection at age, and size of natural mortality (array AE);
(6) the economic weighting factors for each nation and each stock (array AF);
(7) the monthly availability pattern characteristic to each stock—as estimated in Section 2 (array AG).

With these seven blocks of information it is possible to establish a dynamic population model, describing the changes in abundance of the different stocks, under conditions of mobile fishing effort. Table 15 gives the flow chart on which the workings of the model are based.

4.3. THE MODEL PROGRAM

The sequence of operations is as follows. The elements of array AD are taken, one nation at a time, and multiplied by the elements of array AG, a stock at a time, in any one given month. This multiplication calculates the fishing mortality generated by one fishing trip by that nation in that month on each stock in turn. This fishing mortality is then applied to the actual numbers of fish of each age in each stock (array AA) and the stock biological parameters (array AE) according to the following equation:

$$\text{Total catch, by weight,} = \sum_{i=1}^{12} F\,\varepsilon_i\,N_i\,W_i, \qquad (4.1$$

where i = age of cod from 1 to 12;
F = fishing mortality generated by one trip;
ε_i = elements 1–12 of array AE;
W_i = elements 13–24 of array AE;
N_i = elements of array AA, specific to each stock.

To compare the 10 expected catches in economic terms they are converted to economic variables by multiplying by the corresponding elements of the correct nation column of array AF. It is these resulting values that are used as criteria for dividing up the national monthly effort (corresponding element of array AC) between the 10 stocks. The 10 values are added, and each individual value is divided by the sum to give 10 values in percentages. These are multiplied by the element of array AC to give the amount of fishing effort to be applied to each stock.

This procedure is repeated for each of the 15 nations in that month, after which the sum of effort on each stock is applied, and converted to a catch value by the equation:

$$\text{Catch} = \sum_{i=1}^{12} \frac{\varepsilon_i F}{\varepsilon_i F + M} N_i\left(1 - e^{-(\varepsilon_i F + M)}\right) . W_i. \qquad (4.2)$$

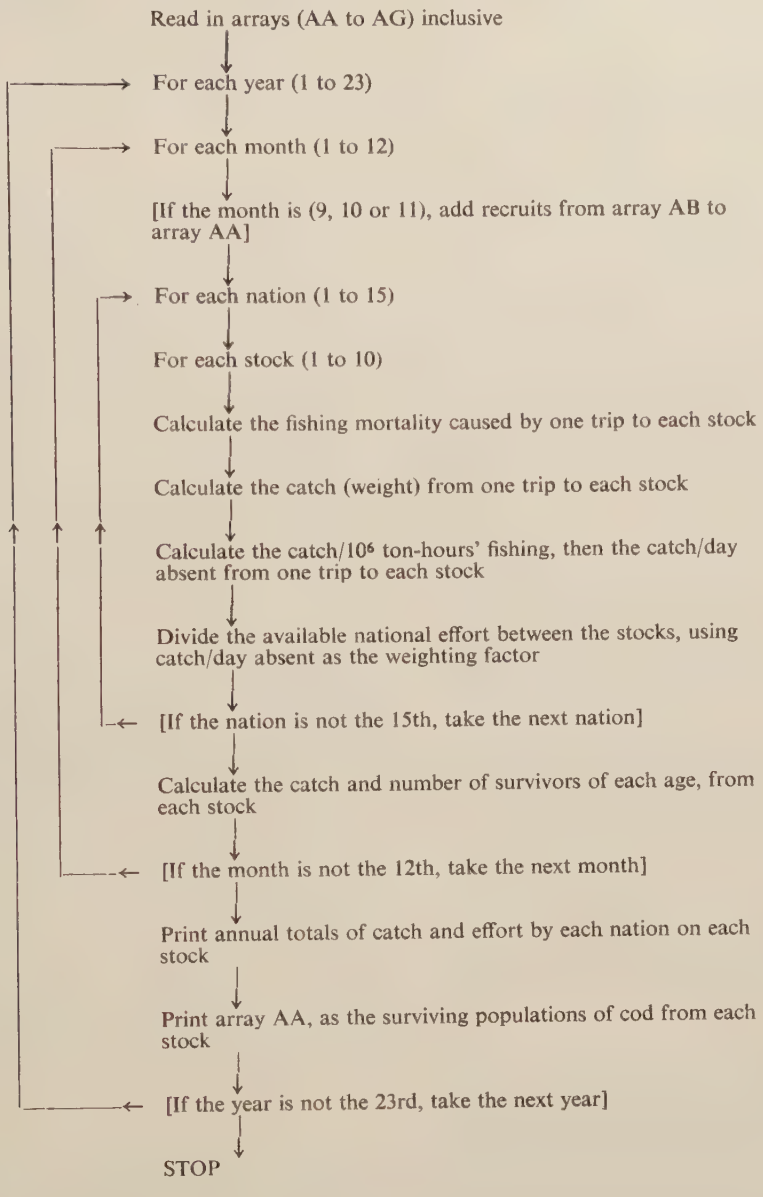
The number of survivors of each age in each stock is computed from:

$$\text{No. of survivors} = N_i e^{-(\varepsilon_i F + M)}. \qquad (4.3)$$

This is substituted back in array AA as the new stock. If the month is the ninth, tenth or eleventh, the corresponding elements of the correct year column of array AB are added to the elements of the first row of array AA, as the influx of one-year-old recruits. The whole procedure is then repeated for the 12 months of that year, after which the catch from and effort on, each stock by each nation in that year is printed out, together with the age-composition of the remaining cod in each stock (i.e. array AA is printed out at the end of each year). The complete plan is repeated for the remaining 22 years, with the required print-outs after each year.

Two remaining complications have to be introduced into the model at this stage. Firstly, data on the five north-west Atlantic stocks have been collected in a relatively complete form only since 1955; previous to that, reliable estimates of catch and effort are not available, although fishing is known to have been quite extensive. This means that the model must be started in 1955 for the north-west Atlantic stocks and in 1946 for the north-east Atlantic stocks. But, at the

15 *Basic flowchart*


Read in arrays (AA to AG) inclusive
For each year (1 to 23)
For each month (1 to 12)
[If the month is (9, 10 or 11), add recruits from array AB to array AA]
For each nation (1 to 15)
For each stock (1 to 10)
Calculate the fishing mortality caused by one trip to each stock
Calculate the catch (weight) from one trip to each stock
Calculate the catch/10⁶ ton-hours' fishing, then the catch/day absent from one trip to each stock
Divide the available national effort between the stocks, using catch/day absent as the weighting factor
[If the nation is not the 15th, take the next nation]
Calculate the catch and number of survivors of each age, from each stock
[If the month is not the 12th, take the next month]
Print annual totals of catch and effort by each nation on each stock
Print array AA, as the surviving populations of cod from each stock
[If the year is not the 23rd, take the next year]
STOP

mencement of the first run, for array AA stocks 1–5 the refer to the age-composition of the north-east Atlantic ks in 1946, and for array AA stocks 6–10 the data refer he age-composition of the north-west Atlantic stocks in 5. Therefore, the program must be altered to prevent ons from fishing the stocks 6–10 during the years 1946–T=1 to 9).

econdly, it must be remembered that stocks 1–3, the to-Norwegian group, are an interconnected complex of mixing stocks and three fisheries. Thus, any fishing on k 2, in the Norway coast area, is actually done jointly on cod stocks 1 and 3, inhabiting the Barents Sea and Bear nd areas, and migrating into the area of stock 2 for wning. There is therefore built into the program a ure that gives stock 2 a zero stock in array AA and zero ruitment in array AB. When fishing effort is applied to k 2, the program assigns that effort to the sum of the ulation of stocks 1 and 3 (as if all the cod had migrated the Norway coast). Any mortality caused by effort on k 2 is subtracted from the populations of stocks 1 and 3, portionate to the size of stocks 1 and 3 at the time. This umes, in effect, that cod from one feeding stock do not rn, after spawning, to the other feeding stock. Recruitment to stock 2 is indirect, as it is in nature, being represented by recruitment to stocks 1 and 3.

The resulting program is given in Appendix 14, written in Fortran IV for an ICL 1907 computer.

4.4. SUMMARY OF THE ACTUAL FORM OF THE DATA

Array AA (Appendix 7) 10 stocks×12 ages This gives the actual number (in millions) of cod of each age from 1 to 12 in each stock 1 to 10 at a given time. Where possible, the original values entered into this array were obtained from age-composition data for the initial year. For most stocks, however, these are lacking, and instead estimates have been obtained from a theoretical age-composition which takes into account the relative strength of year-classes in the stocks at that time as determined from subsequent age analyses of the populations.

Array AB (Appendix 8) 10 stocks×23 years This gives the

actual number (in millions) of one-year-old recruits entering each stock (1 to 10) during September, October and November of each year (1946–68). Recruits are entered in this way to parallel the natural situation in which cod leave the surface waters towards the end of their first year of life. Variation of the number of recruits with time is allowed in this simulation by entering, for each stock, direct estimates of the fluctuations of year-class strengths. It would also be possible to enter hypothetical relationships between recruitment and factors such as temperature, or overall stock density, or density of cod of spawning age.

Array AC (Appendix 9) 15 nations × 23 years This gives the amount of fishing (in million ton-hours' fishing) in the north Atlantic by each nation (1 to 15) in each month over a period of 23 years (1946–68). The figures in this array represent one-twelfth of the calculated annual effort, since it is assumed that each nation's fishing effort is deployed uniformly throughout the year. This simplifies the entering of the effort values into the model.

Array AD (Appendix 10) 15 nations × 1 trip This gives the amount of fishing (ton-hours' fishing) per trip undertaken by each nation. Each nation is given a characteristic trip-length, representing an average trip by that nation to any stock in the north Atlantic.

Array AE (Appendix 11) 10 stocks × 25 parameters This gives some of the stock parameters calculated in Section 3: parameters 1 to 12, the fractional selection (ε_i) of cod of age 1 to 12 years in each stock; parameters 13 to 24, weight at age (in g) of cod in each stock; parameter num 25, the mean monthly natural mortality coefficient for e stock. This important array gives the interaction of the bio gical characteristics of each stock of cod and the fishi gear used.

Array AF (Appendix 12) 10 stocks × 15 nations This gi the nation/stock interaction as a set of economic weight factors converting the catch obtained from a trip by ea nation to each stock into economic variables, the sizes which govern the proportion of each nation's effort to applied to each stock. This array is not orthogonal, since n all of the nations fish all of the stocks. In the simulatio nations are prevented from fishing stocks that they do not fact visit by including zero values in this array.

Array AG (Appendix 13) 10 stocks × 12 months This giv the monthly availability pattern for each stock, as describ in Section 2, expressed in units of q. The fact that natio are not represented in this array assumes that all natio encounter the same availability pattern at any given stoc This may not be true, particularly when the fishing gea used differ, e.g. hand-liners and otter-trawlers may ha different seasonal patterns of effort, because they are fishin different localities but the same overall stock, and catchin different parts of the same population. The predominanc of trawling as a fishing method in most nations suggests tha the use of a single availability pattern for each stock i justified.

Simulations

/ALIDATION OF THE MODEL PARAMETERS

rocedure followed during the preliminary runs of the am was to exclude the dynamic properties of the model, at the accuracy of the parameter estimates might be d. The known annual values of international fishing were applied to each stock in isolation. This was ved by using 10 dummy nations—one to each stock; nation represented all the international fishing fleets ting on one of the stocks. Therefore the size of array as 10×23, each element of the matrix representing the national fishing effort on one of the stocks in one of the . Array AF consisted of a diagonal matrix, with all the ents being zero except the 10 diagonal ones, which were the value 1. Array AG had the annual average value for each stock and each month.

gure 18 gives the set of catch-per-effort estimates ob-ed for the 10 stocks in the first run of the model, super-osed on the actual values obtained by the English fleet e 1946. It may be seen that the change in catch-per-effort time of the north Atlantic cod stocks is described fairly , particularly in the north-east Atlantic stocks. The ap-rance of especially strong year-classes (e.g. the 1949–50 -classes in the Barents Sea) in the international catches w years after recruiting is noticeable in both the actual simulated curves. In the five north-east Atlantic stocks, relations of the 23 pairs of observed and predicted values all significant at the 99.9 per cent level. In the north-west antic stocks, correlations are only significant at south-t Greenland (99.8 per cent) and east Greenland (98 per t). Indeed, at the Labrador/Newfoundland and Grand nk stocks, the correlations are negative (though non-nificant).

The average levels of predicted catch-per-unit effort com-red well with the observed values. For 7 of the 10 stocks, reement was to within 10 per cent. The Norway coast had average catch-per-effort that was 17 per cent too low, ile those of the two other Arcto-Norwegian stocks were -25 per cent too high. These differences may be connected th the construction of the model of these three inter-nnected stocks.

The model predicts a long-term decline in catch-per-effort th time, associated with the increasing level of fishing ort on all the stocks. The observed catch-per-effort at brador/Newfoundland and Grand Bank, however, has mained level or even increased during 1955–69, a period of ctuating, but generally increasing, effort on those stocks. his discrepancy suggests that the values of catch-per-effort ay not be indices of the true abundance of cod in these ocks. There may have been changes in availability, so that though the amount of fishing gear present on two separate casions was identical, the fishing mortality caused by it ay have been completely different. This is not entirely un-pected, since the north-west Atlantic stock areas have ore severe oceanographic conditions than the north-east tlantic stock areas. For example, annual variations in the osition of the ice limit at Greenland and Labrador may ffect the distribution of fish, and certainly affects the distri-ution of the fishing fleets, thereby altering the proportion f the population that is at risk to capture at any time.

5.2. APPLICATION OF THE FIXED EFFORT MODEL

A possible use of the model in this fixed form may be illustrated by examining the future trend in catch and catch-per-unit–effort that it predicts would follow from an assumed pattern of future development in international fishing effort. On the basis of the expansion of total international fishing effort since 1946 an increase of 4 per cent per annum has been assumed for each stock, and the model has been extended to 1975 by incorporating also estimates of recruitment in year-classes already spawned which will contribute to the fisheries in that period (see Table 11). In this run, therefore, the total international fishing effort in the north Atlantic was considered to increase from 2118×10^6 ton-hours in 1969 to 2680×10^6 ton-hours in 1975 (an increase of 27 per cent in 6 years).

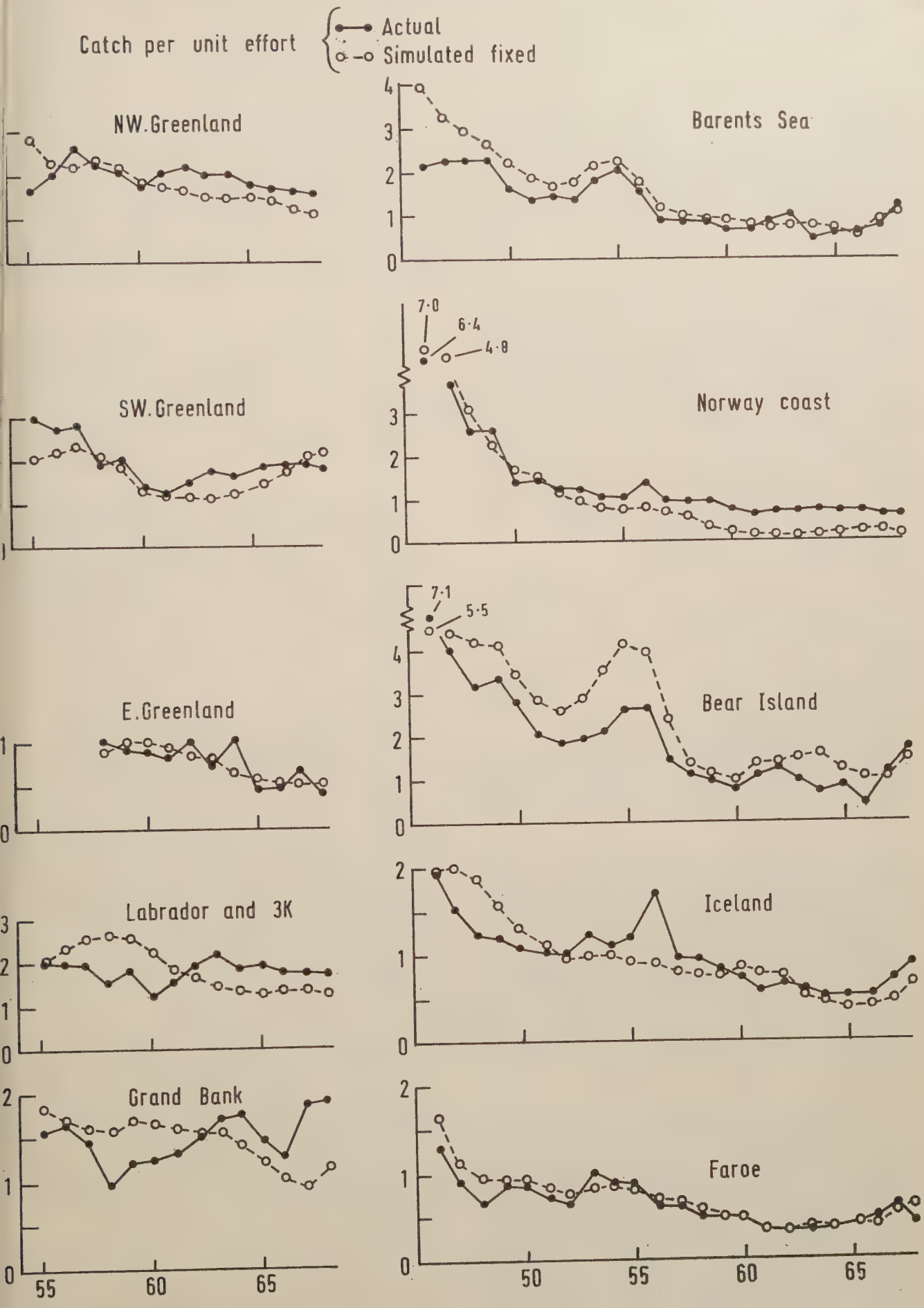
Table 16 gives the predicted values of catch and catch-per-effort for the 10 stocks for the period 1969–75; in most cases the predicted catches were 50–75 per cent smaller in 1975 than in 1969. The only stocks giving increased catches were Iceland and north-west Greenland, possibly in part because below-average year-classes in these stocks had depressed the 1969 catches used as a basis for comparison; the 1959–63 year-classes at Iceland, and the 1962–64 at north-west Greenland, were very poor (see Table 11). For some of these stocks, in the absence of data, it has been assumed in the prediction that future year-classes will be of average strength, and this factor alone has helped to boost the predicted future catches.

Iceland and north-west Greenland were also the only stocks with predicted increased catches-per-effort in 1975 compared with 1969, for the same reason; all the remaining stocks showed marked decreases compared with 1969, particularly the Arcto-Norwegian. By 1975 the Norway coast stock, fished mainly for its mature cod, is reduced to 11 per cent of its 1969 level, and the two feeding stocks are both down to 42 per cent of their level just 6 years earlier. This predicted decrease of the Arcto-Norwegian stock must be due largely to the extremely weak 1966–69 year-classes, too young to enter the catches in 1969 but making their weakness apparent particularly in 1971–73 in the feeding stocks and from 1973 onwards in the Norway coast stock. These poor catches would be expected to continue until a fairly strong set of year-classes again entered the fishery.

No particular significance can be attached to this projection. The 4 per cent assumed rate of increase in effort was based on parity with 1946–66 yet since 1961 (see Figure 7) fishing effort has been relatively static, and recruitment in future years has been assumed. However, it serves to illustrate one application of the model and the results of this or any other future pattern of effort may be investigated in a similar manner to Table 16.

TABLE 16 *Predicted catch (thousand tons round fresh weight) and catch-per-effort (tons/10³ ton-hours' fishing), 1969–75*

Year	Barents Sea		Norway coast		Bear Island		Iceland		Faroe		Greenland						Labrador/ Newfoundland		Grand Bank		Total north Atlantic catch
											north-west		south-west		east						
	Catch	Cpe	Catch	Cpe	Catch	Cpe	Catch	Cpe	Catch	Cpe	Catch	Cpe	Catch	Cpe	Catch	Cpe	Catch	Cpe	Catch	Cpe	
1969	579	1.07	28	0.09	263	1.58	145	0.82	36	0.56	189	1.08	98	1.88	19	0.46	367	1.06	356	1.40	2080
70	391	0.69	32	0.10	207	1.20	170	0.93	35	0.52	217	1.19	85	1.58	19	0.44	320	0.89	360	1.36	1836
71	191	0.32	43	0.13	103	0.57	187	0.98	34	0.48	247	1.30	78	1.38	19	0.42	286	0.77	336	1.22	1524
72	111	0.18	37	0.11	51	0.27	199	1.00	34	0.45	269	2.36	73	1.24	19	0.40	268	0.69	311	1.09	1372
73	165	0.26	19	0.05	50	0.26	105	1.00	33	0.43	282	1.37	68	1.13	19	0.39	264	0.66	285	0.96	1390
74	250	0.38	7	0.02	94	0.47	208	0.97	32	0.40	290	1.36	65	1.03	19	0.38	262	0.63	266	0.86	1493
75	309	0.45	3	0.01	141	0.67	209	0.94	32	0.38	294	1.32	65	0.99	19	0.36	262	0.60	251	0.78	1585
1975 cpe / 1969 cpe ×100(%)		42		11		42		115		68		122		53		78		57		56	



. 18 Comparison of changes in the actual catch-per-effort of the English fleet since 1946 with those predicted by the computer simulation (fishing effort fixed).

5.3. SIMULATION WITH MOBILE FISHING EFFORT

The next step in the model is to attempt a dynamic simulation of the 10 north Atlantic stocks over the period 1946–68. The elements of array AE were the national values of fishing effort applied to the 10 north Atlantic stocks in any one year. The relevant economic weighting factors described earlier in this section were inserted into array AF. Seasonal variation about the annual average value of q for each of the stock was incorporated into array AG.

It was soon discovered that the inclusion of the large amount of Norway's offshore fishing effort into a mobile Norwegian fleet resulted in a virtual boycotting of the local stock because of the low stock abundance when expressed in terms of the catch-per-unit-effort of English vessels trawling offshore. Since approximately half of Norway's fishing effort in the north Atlantic is composed of small vessels of very restricted range, it is regularly applied to the Norway coast fishery, and it was therefore necessary to force half of this fishing effort to go to the Norway coast (termed Norway *inshore*), while allowing the other half to visit any of the stocks that it normally visits. This device established the correct level of Norwegian fishing effort at the Norway coast.

It was also necessary to prevent any nation from fishing a stock that it visits only occasionally. This was done because a disproportionate amount of national fishing effort was often attracted to these stocks—the very ones for which national catch and effort data were weakest. Therefore a level of 1 per cent was chosen, such that if a nation expended less than 1 per cent of its average annual north Atlantic fishing effort on any stock, it was considered not to visit that stock. In this way USSR was prevented from fishing north-west Greenland, Spain was prevented from fishing south-west Greenland, England was prevented from fishing east Greenland and Labrador/Newfoundland, and Germany and Norway were prevented from fishing the Grand Bank stock.

Figure 19 gives the results of the simulation, in the amount of effort attracted to each of the 10 stocks as compared with the observed values. Correlation between observed and predicted values is significant at the 99.9 per cent level for four of the five north-east Atlantic stocks, and in the remaining one (Bear Island) at 99.8 per cent. In the north-west Atlantic, four of the five stocks have significant correlations at different levels, varying from 99.9 per cent at Labrador/Newfoundland to 95 per cent at north-west and south-west Greenland. The Grand Bank stock gave a non-significant correlation.

Comparison of the actual amounts of fishing effort attracted to the different stocks was made using 1955–69 averages. In this simulation, Norway coast, Faroe and north-west and east Greenland attracted fishing effort to within 10 per cent of the observed levels. The other stocks showed the following differences, first as a percentage and then in million ton-hours: Barents Sea, −32 per cent, 157; Bear Island, +24 per cent, 39; Iceland, −26 per cent, 62; south-west Greenland, +121 per cent, 46; Labrador/Newfoundland, +33 per cent, 61; Grand Bank, +38 per cent, 71.

It is interesting to note that the simulation caused the Barents Sea to attract 32 per cent too little effort and Bear Island 24 per cent too much. Although these amounts of fishing effort do not cancel each other out (because of the great difference in the amount of fishing effort applied to the two stocks) it may be that the economic weighting factors applied to these two related stocks were incorrect. In the simulation Norway and USSR were principally responsible for the imbalance between these stocks, by concentrating too much on Bear Island. A re-examination of the factors determining which of the two neighbouring stocks is visited by the fishing vessels of these two nations (whose coasts border the stocks) may suggest logical alterations in the weighting factors applied. Among the north-west Atlantic stocks south-west Greenland attracted more than twice as much fishing effort in the simulation as in the actual situation. This was mainly due to excessive English, French and Portuguese attention.

In the simulation an average of 190 million ton-hours extra fishing was applied to the north-west Atlantic stocks out of an annual north Atlantic total of 1750×10^6 ton-hours; i.e., the proportion of north Atlantic fishing effort applied to the five north-west Atlantic stocks in the simulation was approximately 45 per cent compared with the observed 34 per cent.

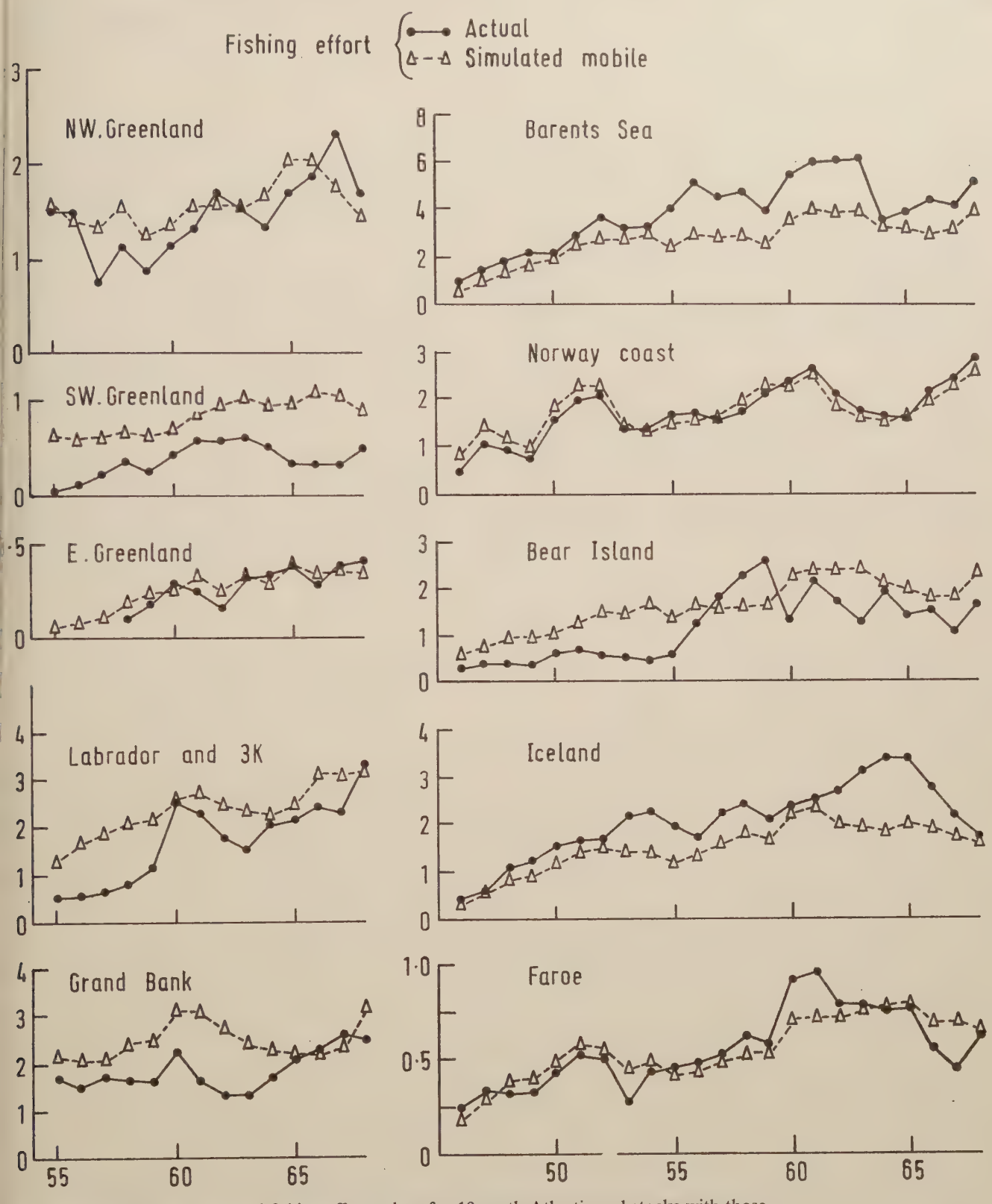
Given the limitations of the data for some north-west Atlantic stocks the agreement between the simulated and the historic record does indicate that the parameters incorporated in the model are sufficient to account for most of the observed variation in the cod fisheries. The results do however point to several aspects of the model that merit further examination. Firstly, a large proportion of the discrepancies may be thought to reflect errors in the economic weighting factors, because these have been based upon English trawler data alone.

Secondly, one of the factors that may be critical to the distribution of fishing effort is the assumed proportionality between the expected value of the catch per day absent and the amount of fishing effort that it attracts. It became apparent that the distribution of fishing predicted by the model was more uniform than the actual distribution; stocks that normally attract a small amount of a nation's effort tended to attract a great deal of effort. There may be evidence to suggest a different relationship (perhaps a power factor) between catch per day absent and fishing effort. Linked with this is a second assumption in the model that the entire fishing capacity deployed on those fisheries is technically capable of fishing on any one of them according to fishing prospects. It is by no means certain that this was so, particularly during the 1955–65 period.

The assumptions proposed as possible sources of error were initially taken to keep the model as simple as possible. However, the model has been constructed so that further refinements of parameters can be incorporated without difficulty. For instance, it may be considered desirable to incorporate time-varied data matrices for some of the attributes that have so far been taken to remain constant, such as the proportion of national fleets with total mobility, and growth rate.

5.4. POSSIBLE APPLICATIONS OF THE MODEL

During the period in which this research was undertaken it was possible only to demonstrate the possible predictive



19 Comparison of the observed fishing effort values for 10 north Atlantic cod stocks with those predicted by the computer simulation (fishing effort mobile).

ıe of the model. Given appropriate improvements indi-
ed in Section 5.3 this may be of value in anticipating
ıds in the north Atlantic cod fisheries. Equally important,
data input arrays have been chosen to permit flexibility
valuating management strategies. For example, it would
possible to test the longer-term implications of many of
management measures at present available to the regula-
Commissions. Changes in mesh regulation in any com-
ation of mesh size or stocks may be investigated by
ustment of the fractional selection coefficient in array AE.
ilarly, the effects of seasonal or total stock closures are accessible through array AG, and limitation of fishing effort through array AC.

Future development of the model may also permit the evaluation of possible relationships between spawning stock and subsequent recruitment, and investigations to assess the optimal distributions of national fishing effort on a north Atlantic scale. It is also thought that the general model might have applications to fisheries on species mixed within geographical areas, where the same level of physical fishing effort may exert differing levels of fishing mortality according to interspecific differences in the availability coefficient.

Summary

e first three sections of this paper, deterministic yield ls were fitted to 10 north Atlantic cod stocks. By giving s to biologically meaningful parameters, these pre- l the magnitude of steady-state yields obtained under ent levels of fishing effort.

Section 4 a computer model was assembled to put the dividual stock models into the wider context of the Atlantic. By preventing movement of international g effort between the stocks, it was possible then to late the change in catch-per-effort with time within each , and to predict future changes in catch under an ned rate of increase in fishing effort.

ble 16 in Section 5 suggests that catches from most of north Atlantic stocks cannot be increased greatly, and tained at a higher level, by further increases in fishing t. In fact, under these circumstances the catch-per-effort es must fall noticeably. The results given in Table 16 an example of the sort of prediction that is possible, using the model. Different rates of growth (or contraction) of total international effort may be assumed, and results similar to those in Table 16 obtained.

The dynamic simulation described at the end of Section 5 is potentially the most interesting simulation. It is thought that differences between the observed and predicted levels of fishing effort on each stock could be reduced by further research into national economic weighting factors and into the assumptions determining the distribution of fishing effort.

The results outlined in Section 5 also showed that the number of recruits is an important factor in the model. Any increase in the accuracy of prediction of year-class strengths, perhaps by echo sounding surveys on the young fish, could pay great dividends in more accurate assessments of the effect of various management strategies that may be tested using the model.

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APPENDIX 1 *National cod catch (10^3 metric tons round fresh weight) from each stock (1–10) in each year (1946–68)*

	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968
BARENTS SEA (1)																						0.82	
Germany		6.00	16.94	17.22	13.52	16.14	8.20	2.34	12.45	14.87	11.65	7.59	1.18	0.25	0.35	0.82						118.31	119.22
Norway	28.68	53.12	63.39	67.82	66.23	66.85	92.02	101.42	86.76	126.04	113.69	117.12	153.69	116.42	100.65	116.48	89.70	91.70	61.40	116.76	100.62	48.22	94.69
England	53.84	127.24	164.79	226.45	136.79	129.03	130.55	59.45	72.35	91.74	67.79	38.49	46.23	54.95	70.68	73.97	84.52	66.25	24.04	27.29	47.12	155.42	428.54
USSR	117.10	151.97	158.65	162.34	135.41	189.58	258.83	261.40	404.65	530.28	512.17	183.00	146.57	119.90	178.80	199.49	350.56	367.11	112.81	97.43	138.64		
Others	0.03	2.43	2.85	11.12	4.52	6.38	34.56	18.23	21.32	67.77	81.78	53.40	40.40	31.28	30.00	16.93	15.00	15.00	8.36	4.55	10.08		
Total	199.65	340.76	406.62	484.95	356.47	407.98	524.16	442.84	597.53	830.70	787.08	399.60	388.07	322.80	380.48	407.69	539.78	540.06	206.61	246.03	296.46	322.77	642.45
NORWAY COAST (2)																							
Germany		1.19	15.74	11.28	14.32	17.00	16.42	12.49	8.01	14.80	27.14	14.44	15.99	13.23	8.69	7.04	6.29	4.09	3.20	3.67	4.30	2.81	1.07
Norway	275.50	329.64	176.88	145.52	173.78	238.51	195.52	113.30	104.49	129.74	176.56	95.20	112.94	143.72	120.04	124.13	109.23	93.21	76.11	72.82	96.35	97.06	131.93
England	20.41	45.30	43.77	30.48	15.48	22.99	33.89	23.30	17.33	19.17	28.38	26.82	23.20	22.10	26.10	17.67	22.71	19.53	24.64	22.02	32.64	28.19	29.36
Others		0.25	0.45	0.80	8.15	0.19	0.95				0.08				0.82	0.04			8.97	5.01	6.46	0.67	0.11
Total	295.91	376.38	236.84	188.08	211.73	278.69	246.78	149.09	129.83	163.71	232.16	136.46	152.13	179.05	155.65	148.88	138.23	116.83	112.92	103.52	139.75	128.73	162.47
BEAR ISLAND (3)																							
Germany	19.11	14.75	5.31	9.55	0.74	3.05	0.30	4.39	0.29	2.86	30.28	23.14	3.31	0.22									
Norway	4.65	9.66	8.70	6.15	7.73	9.69	9.74	4.16	4.78	12.61	45.70	37.39	15.47	23.75	12.61	27.77	26.68	16.81	12.37	7.50	6.82	3.53	4.46
England	185.80	136.63	107.54	104.67	96.44	103.63	60.55	50.65	58.51	104.42	164.04	89.33	80.09	100.76	44.39	66.27	67.74	44.07	45.88	40.56	18.79	10.60	16.00
USSR	0.88	3.85	9.28	5.89	53.67	21.26	25.80	34.38	30.34	22.14	69.32	99.84	99.10	80.49	34.60	126.29	126.20	50.58	67.74	55.35	30.66	106.91	248.22
Others				0.85	5.20	2.86	9.48	10.04	4.76	11.41	14.49	6.80	31.15	37.56	9.99	2.13	1.99	5.03	7.69	10.76	2.16		0.22
Total	210.44	164.89	130.83	127.11	163.78	140.49	105.87	103.62	98.68	153.44	323.83	256.50	229.12	242.78	101.59	222.46	222.61	116.49	133.68	114.17	58.43	121.04	268.90
ICELAND (4)																							
Faroe	15.00	15.00	15.00	15.00	15.00	15.00	15.51	16.22	15.37	18.67	16.19	20.92	17.88	7.68	11.78	10.60	8.66	6.25	6.89	5.25	3.41	2.77	4.26
Germany	11.01	10.82	11.19	24.12	30.33	33.81	41.81	56.01	45.25	48.24	30.07	23.29	37.85	35.56	37.94	21.78	34.16	33.03	19.34	14.98	10.49	14.35	27.96
Norway	0.19	0.06	0.01	0.11	0.89	3.83	4.11	7.47	7.22	7.05	4.58	8.23	6.83	5.46	3.43	4.21	4.70	3.51	2.69	0.42	0.47	0.18	0.28
England	36.85	52.37	90.70	91.13	108.90	103.49	94.57	173.80	165.69	138.71	127.79	144.27	150.52	112.74	109.41	96.54	105.14	123.19	122.21	128.14	109.04	126.57	111.57
Belgium	0.89	5.15	3.18	4.39	4.25	5.59	4.94	7.63	6.22	9.00	6.98	6.75	9.95	5.46	5.56	5.43	8.20			3.75	2.69	2.37	3.49
Scotland	4.76	4.07	4.15	4.95	5.22	2.65	1.56	1.42	1.47	1.03	2.53	1.36	1.20	1.35	1.24	2.07	3.11	3.18	4.58	6.78	4.73	3.61	2.83
Others	0.03	1.91	3.08	1.55	1.34	0.87	0.13	0.01	0.12				0.06			0.15	0.55			0.76	2.59	0.37	1.48
Total	68.73	89.38	127.31	141.25	165.93	165.24	162.63	262.56	241.34	222.70	188.14	204.82	224.29	168.25	169.36	140.78	164.52	169.16	155.71	160.08	133.42	150.22	151.87

APPENDIX 1 (*continued*)

	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968
	FAROE (5)																						
Faroe	5.00	5.00	5.00	5.00	5.00	5.00	4.55	4.14	5.19	7.90	7.94	6.92	6.54	4.68	8.72	9.52	6.75	7.43	8.89	9.95	7.96	7.83	13.76
England	14.33	14.59	6.59	11.67	15.82	15.96	12.27	12.27	15.96	17.10	8.34	10.04	9.83	9.99	13.43	3.82	5.21	4.46	5.80	5.48	3.99	7.11	7.10
Scotland	9.35	8.54	7.70	9.81	13.65	13.39	12.46	9.83	14.04	11.71	9.55	12.28	9.47	9.70	14.73	11.73	10.48	10.18	6.91	7.04	7.44	8.55	8.46
Others	1.80	2.85	1.42	1.65	1.50	0.68	0.94	0.82	0.98	1.87	1.80	2.14	1.96	1.45	2.34	1.88	1.74	2.05	3.38	4.74	3.54	2.37	4.77
Total	30.48	30.98	20.71	28.13	35.97	35.03	30.22	27.06	36.17	38.58	27.63	31.38	27.80	25.82	39.22	26.95	24.18	24.12	24.98	27.21	22.93	25.86	34.09
	NORTH-WEST GREENLAND (6)																						
Faroe										29.40	31.41	32.12	42.18	37.15	50.28	56.41	89.23	77.79	70.00	65.46	64.53	63.68	45.81
France										33.67	29.83	22.42	22.85	29.32	20.96	38.69	52.05	35.52	33.82	39.16	39.38	42.02	38.88
Germany										6.90	28.40	8.18	20.82	11.95	13.34	63.19	93.80	91.94	66.61	84.27	60.53	106.22	77.67
Norway										28.36	27.77	10.11	23.45	14.42	17.51	29.78	28.53	22.72	23.03	21.16	25.57	45.21	33.00
Portugal										103.70	105.41	76.42	81.64	49.85	52.45	67.34	89.07	61.72	53.21	60.67	74.49	62.70	26.32
Spain										7.45	30.15	17.28	23.77	11.93	3.83	1.33	2.98	0.38	0.54	0.65	3.53	7.68	20.74
England										1.15	1.39	0.93	2.92	4.72	3.87	5.58	9.46	16.13	13.34	7.76	8.24	14.73	5.56
USSR															1.43			4.07		0.87	0.22	0.57	1.49
Dummy 1										34.99	35.56	35.16	31.32	18.34	16.23	10.19			5.35	17.09	28.66	26.70	11.51
Total										245.62	289.92	202.62	248.95	177.68	179.90	272.51	365.12	310.27	265.90	297.09	305.15	369.51	260.98
	SOUTH-WEST GREENLAND (7)																						
France										0.46	0.64	4.78	0.87	1.06	0.05	0.74		0.67	0.98	0.93	2.03	1.33	7.71
Germany										0.34	0.68	1.05	7.81	2.75	6.88	20.36	31.10	44.85	27.93	20.46	21.70	32.28	55.55
Norway										14.61	13.20	9.80	13.02	12.19	14.27	13.71	3.39	9.25	11.56	10.90	13.17	7.98	6.65
Portugal										0.01	3.56	20.51	18.65	7.90	5.43	0.41	2.58	1.51		0.01	0.23	+	6.44
Spain											1.40	5.60	3.23	1.79	0.10	0.01	0.43	0.10	0.20		0.04	2.98	0.95
England										3.89	1.60	8.64	6.46	7.49	8.05	2.66	6.48	10.54	13.47	6.09	11.20	5.21	4.73
USSR															0.06			0.99					0.46
Dummy 2										0.38	10.26	15.87	19.84	22.68	26.59	35.01	46.82	40.77	29.70	24.83	12.60	9.77	10.07
Total										19.69	31.34	66.25	69.88	55.86	61.43	72.90	90.80	108.68	83.84	63.22	60.97	59.55	92.56
	EAST GREENLAND (8)																						
Germany													5.92	12.60	19.07	15.02	14.30	13.88	30.62	10.97	7.79	12.12	8.32
England															0.27	0.80	1.75	0.73	0.96	0.93	0.23	1.38	+
Dummy 3													5.00	6.58	4.57	3.87	1.25	8.45	4.00	5.60	4.86	11.23	7.35
Total													10.92	19.18	23.91	19.69	17.30	23.06	35.58	17.50	12.88	24.73	15.71

APPENDIX 1 (*continued*)

	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968
LABRADOR/NEWFOUNDLAND (9)																							
France										7.62	12.35	12.72	17.76	23.75	60.59	54.57	53.73	52.49	57.15	39.64	48.85	52.74	64.80
Germany															4.46	10.59	0.45	1.26	4.52	40.06	65.01	32.60	54.12
Portugal										13.62	15.20	8.66	15.39	34.71	59.81	65.09	75.50	103.44	79.30	85.95	52.00	65.74	72.85
Spain										0.01	0.29	0.83	10.82	30.17	41.97	53.27	66.51	65.48	72.86	69.43	57.37	46.54	46.67
England														2.04	0.98	1.60	4.09	0.62	1.85	14.02	15.99	17.54	23.23
USSR															64.60	117.95	71.36	37.10	72.17	57.45	35.84	29.97	137.65
Dummy 4										86.53	86.07	97.81	73.07	112.80	77.33	55.24	73.43	82.84	89.85	102.22	152.58	154.60	163.08
Total										107.78	113.91	120.02	117.04	203.47	309.74	358.31	345.07	343.23	377.70	408.77	427.64	399.73	562.40
GRAND BANK (10)																							
Faroe												2.96	3.94	7.58	9.62	5.47	4.51	13.85	21.69	14.19	14.85	15.49	17.04
France															16.50	14.03	26.76	12.11	31.61	27.17	23.18	25.12	17.28
Germany															0.12	0.04		1.60	0.28	7.10	6.30	0.91	
Norway											1.18	16.17	6.30	4.01	4.50	3.00	1.80	4.85	6.84	0.04		4.01	23.79
Portugal										64.10	64.57	64.02	27.67	37.23	34.31	34.68	25.79	39.15	58.46	33.37	48.86	88.39	95.23
Spain										61.35	57.30	61.00	37.50	48.14	47.20	53.72	51.14	63.28	71.93	95.79	85.22	137.52	154.05
England											0.97	0.67		1.48	6.12	3.57	3.16	7.78	9.87	15.12	10.69	25.25	11.10
USSR															60.88	23.07	7.29	14.65	5.92	13.76	39.91	122.38	79.58
Dummy 5										148.59	128.71	115.32	83.37	103.31	103.44	83.55	81.41	75.37	94.84	87.93	58.47	60.96	67.59
Total										274.04	252.73	260.14	158.78	201.75	282.69	221.13	201.86	232.64	301.44	294.47	287.48	480.03	465.66

APPENDIX 2 *Annual catch per effort values for each nation*

	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968
BARENTS SEA (1)																							
Germany (m tons per day fished)			19.910	16.998	15.778	11.048	5.383	7.009	14.635	14.160	13.612	12.321	7.030		1.671	6.746							
England (m tons per hour fished)	1.000	1.213	1.314	1.413	0.929	0.702	0.681	0.627	0.832	0.915	0.768	0.549	0.539	0.587	0.476	0.525	0.623	0.579	0.391	0.452	0.519	0.579	0.849
USSR (m tons per hour fished)	1.130	1.020	0.980	0.950	0.840	0.820	1.050	0.950	1.190	1.420	1.040	0.510	0.460	0.440	0.420	0.380	0.590	0.600	0.370	0.390	0.420	0.530	0.930
NORWAY COAST (2)																							
Germany			6.209	4.340	3.603	4.525	3.801	4.063	2.930	3.532	6.468	3.725	4.652	4.201	2.665	2.216	3.448	3.080	3.542	2.505	2.806		
England	3.195	1.927	1.473	1.597	0.805	0.851	0.719	0.725	0.619	0.650	0.883	0.601	0.574	0.560	0.444	0.389	0.451	0.464	0.478	0.476	0.486	0.383	0.409
BEAR ISLAND (3)																							
Germany			17.697	20.765	15.102	18.047	2.398	13.765	4.042	20.898	18.659	10.568	5.435	5.244									
England	4.676	2.222	1.735	1.995	1.552	1.110	1.108	1.104	1.129	1.453	1.524	0.875	0.801	0.805	0.711	0.866	0.944	0.691	0.652	0.790	0.568	0.763	1.217
USSR		0.870	1.110	0.920	1.290	1.230	0.980	1.190	1.560	1.640	1.710	0.840	0.690	0.550	0.310	0.440	0.740	0.550	0.390	0.490	0.190	0.870	1.030
ICELAND (4)																							
Germany	5.065	3.785	3.005	3.389	3.426	3.395	3.564	4.195	3.341	4.619	3.620	2.781	3.837	4.096	3.899	2.794	4.302	3.946	2.105	1.479	1.051		
England	0.797	0.613	0.541	0.542	0.488	0.494	0.520	0.659	0.621	0.644	0.649	0.541	0.535	0.453	0.408	0.321	0.325	0.327	0.305	0.327	0.347	0.411	0.525
Scotland (m tons per hour fished)									0.258	0.227	0.350	0.263	0.218	0.227	0.148	0.092	0.102	0.092	0.102	0.134	0.175		
Belgium (m tons per hour fished)									0.149	0.175	0.126	0.094	0.134	0.084	0.074	0.076	0.241	0.099	0.063	0.068	0.055		
FAROE (5)																							
England	0.282	0.214	0.148	0.213	0.204	0.164	0.143	0.311	0.219	0.258	0.163	0.165	0.128	0.133	0.132	0.077	0.095	0.097	0.116	0.123	0.134	0.224	0.198
Scotland	0.219	0.136	0.113	0.143	0.143	0.130	0.141	0.129	0.169	0.148	0.131	0.141	0.114	0.108	0.100	0.087	0.073	0.078	0.092	0.104	0.118	0.155	0.146

APPENDIX 2 (*continued*)

	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968
NORTH-WEST GREENLAND (6)																							
France										37.066	32.451	27.460	24.291	21.046	24.066	28.053	30.682	20.613	25.884	25.033	26.875	32.220	
(m tons per day fished)																							
Germany										11.723	31.385	17.102	17.569	17.321	18.479	15.140	21.058	18.848	17.233	18.606	19.005	24.190	
Portugal											3.253	2.575	1.875	1.466	1.951	1.970	2.269	1.834	1.926	2.058	2.398	2.675	
(m tons per hour fished)																							
Spain										3.128	3.168	1.604	1.952	1.086	1.071	1.306	1.267			0.931	2.562	2.374	
(m tons per hour fished)																							
England										0.512	0.682	1.751	1.397	1.874	0.924	1.539	1.301	1.653	1.570	1.102	0.943	1.535	
USSR															0.929			0.623		0.839	0.228	1.433	
SOUTH-WEST GREENLAND (7)																							
France												27.148	23.487	21.180						11.675	37.611	31.560	
Germany											9.988	25.072	22.248	22.211	18.902	11.703	14.573	19.767	15.840	15.296	14.248	16.980	
Portugal											5.789	3.556	3.229	2.298	2.190		1.285	2.401					
Spain											2.431	2.477	1.762	1.425			0.955						
England										2.095	1.803	1.670	1.065	1.438	0.946	0.916	1.104	1.170	1.205	1.559	1.696	0.820	
USSR																		1.431					
EAST GREENLAND (8)													8.506			6.922	8.562	6.348	9.331	4.024	4.269	5.953	
Germany																0.855	1.384	0.493	0.694	0.736	0.709		
England																							
LABRADOR/NEWFOUNDLAND (9)																							
France										28.335	27.198	28.587	22.222	27.712	30.707	29.120	37.760	35.635	32.807	28.977	26.634	24.956	
Germany															24.653	17.593	17.920	13.278	9.926	30.031	29.532	26.220	
Portugal										1.323	1.636	1.322	1.142	1.446	1.825	1.539	1.875	1.965	1.660	1.887	2.008	1.914	
Spain											1.124	0.995	1.121	1.212	1.480	1.372	1.802	1.829	1.765	1.503	1.562	1.672	
England														1.168	0.697	1.676	1.769	1.179	0.768	1.563	1.294	1.187	
USSR															0.347	0.868	0.878	0.972	0.961	1.025	0.791	0.969	
GRAND BANK (10)															28.649	31.394	34.796	31.062	32.420	26.608	24.221	28.009	
France																		32.090		10.768	14.459	15.103	
Germany										1.437	1.740	1.527	1.123	1.171	0.973	1.317	1.387	1.610	1.511	1.143	1.514	1.860	
Portugal										1.014	1.054	0.958	0.640	0.858	0.979	1.089	1.112	1.512	1.425	1.538	1.367	1.486	
Spain											0.899	1.644		1.066	1.002	0.943	1.057	1.197	1.064	0.952	0.889	0.933	
England															0.783	0.471	0.497	0.480	0.542	0.258	0.409	1.035	
USSR																							

APPENDIX 3 *National fishing effort (10^6 ton-hours' fishing) on each stock (1–10) in each year (1946–68)*

	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968
BARENTS SEA (1)																							
Germany		1.6	5.1	6.2	5.3	9.2	9.8	2.2	5.7	7.1	5.9	4.3	1.2	0.1	2.1	0.9						1.0	
Norway	14.3	22.3	25.1	25.4	38.5	52.4	75.6	92.2	60.5	81.3	88.8	130.1	176.8	125.0	135.3	144.2	95.0	106.1	106.5	177.4	133.0	146.7	102.9
England	26.9	53.5	65.2	84.9	79.5	101.1	107.4	54.0	50.4	58.9	53.0	42.8	53.2	59.0	95.0	91.5	89.5	76.7	41.6	41.5	62.9	59.8	81.8
USSR	50.0	71.4	83.2	90.1	86.4	126.5	140.0	153.9	197.2	218.3	294.0	219.6	198.4	170.1	275.2	344.5	402.6	415.4	206.7	171.6	228.8	210.6	337.7
Others (include in Norway)	0.0	1.0	1.1	4.2	2.6	5.0	28.4	16.6	14.9	43.7	63.9	59.3	46.5	33.6	40.3	21.0	15.9	17.4	14.5	6.9	14.8		
Total	91.2	149.8	179.7	210.8	212.3	294.2	361.2	318.9	328.7	409.3	505.6	456.1	476.1	387.8	547.9	602.1	603.0	615.6	369.3	397.4	439.5	418.1	522.4
NORWAY COAST (2)																							
Germany		3.1	15.2	15.8	24.7	23.8	27.8	20.2	18.2	28.5	29.0	27.2	24.5	22.8	24.0	23.8	13.9	10.2	7.2	12.1	12.5	5.3	1.9
Norway	43.1	87.2	62.4	48.3	116.5	154.1	152.3	89.1	97.9	117.7	120.0	96.6	122.0	161.7	173.0	207.4	159.8	134.6	109.9	109.7	141.0	181.7	233.5
England	3.2	12.0	15.4	10.1	10.4	14.9	26.4	18.3	16.2	17.4	19.3	27.2	25.0	24.9	37.7	29.5	33.2	28.2	35.6	33.2	47.8	52.8	52.0
Others (include in Norway)		0.1	0.2	0.3	5.5	0.1	0.7				0.0				1.2	0.1			12.9	7.5	9.5	1.3	0.2
Total	46.3	102.4	93.2	74.5	157.1	192.9	207.2	127.6	132.3	163.6	168.3	151.0	171.5	209.4	235.9	260.8	206.9	173.0	165.6	162.5	210.8	241.1	287.6
BEAR ISLAND (3)																							
Germany	5.0	6.4	1.8	2.8	0.3	1.1	0.8	2.1	0.5	0.9	11.2	15.4	4.3	0.3									
Norway	0.5	2.2	2.6	1.6	2.7	4.8	4.9	2.1	2.4	5.1	18.0	26.1	12.0	18.6	11.3	20.9	18.6	16.3	13.3	7.6	8.7	3.4	2.7
England	19.9	31.4	32.2	27.8	33.6	51.3	30.6	26.1	30.0	42.4	64.6	62.3	6.20	78.8	40.0	49.7	47.3	42.7	49.5	41.3	24.1	10.1	9.5
USSR	2.5	2.5	5.2	5.3	21.6	11.0	16.8	17.1	11.6	5.9	24.0	73.2	111.6	132.3	70.4	143.0	105.6	60.3	122.1	81.6	117.5	89.4	147.9
Others (include in Norway)	1.8			0.2	1.8	1.4	4.8	5.2	2.4	4.6	5.7	4.7	24.1	29.4	9.0	1.6	1.4	4.9	8.3	11.0	2.8		0.1
Total	29.7	42.5	41.8	37.7	60.0	69.6	57.9	52.6	46.9	58.9	123.5	181.7	214.0	259.4	130.7	215.2	172.9	124.2	193.2	141.5	153.1	102.9	160.2

APPENDIX 3 (*continued*)

	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968
	ICELAND (4)																						
Faroe	7.5	10.0	11.6	11.9	13.5	13.7	13.7	11.6	11.9	14.2	12.5	19.7	17.4	9.0	16.0	18.2	14.9	10.9	13.1	9.5	5.7	4.0	4.7
Germany	10.0	13.5	18.0	35.2	44.8	51.6	62.1	72.2	74.8	58.9	47.8	49.2	59.0	53.0	60.5	49.3	51.2	54.9	61.3	68.0	66.2	20.8	31.2
Norway	0.1	0.0	0.0	0.1	0.8	3.5	3.6	5.3	5.6	5.4	3.5	7.8	6.6	6.4	4.5	7.2	8.1	6.1	5.1	0.8	0.8	0.3	0.3
England	18.5	35.0	70.4	72.3	98.2	94.3	83.7	124.0	128.0	105.6	98.4	136.0	146.3	132.0	144.9	165.4	181.2	214.8	232.4	231.4	181.0	183.8	124.3
Belgium									3.9	5.3	6.0	6.3	7.0	5.4	7.3	8.4	1.3	8.6	6.8	7.8	6.8	3.4	3.9
Scotland									0.8	0.7	1.6	1.2	1.3	1.2	1.7	5.4	7.6	9.0	12.3	13.9	7.5	5.2	3.2
Others (include in Faroe)	0.0	1.3	2.4	1.2	1.2	0.8	0.1	0.0	0.1				0.1			0.2	0.9			1.4	4.3	0.5	1.6
Total	36.1	59.8	102.4	120.7	158.5	163.9	163.2	213.1	225.1	190.1	169.8	220.2	237.7	207.0	234.9	254.1	265.2	304.3	331.0	332.8	272.3	218.0	169.2
	FAROE (5)																						
Faroe	4.4	6.0	8.9	6.4	6.9	8.8	9.4	4.0	7.3	9.7	15.8	14.0	17.4	12.2	23.5	44.9	26.3	28.9	29.5	31.8	19.8	12.7	25.2
England	12.7	17.6	11.8	15.0	21.7	28.0	25.3	12.0	22.6	21.1	16.6	20.2	26.2	26.2	36.0	18.0	20.2	17.3	19.2	17.5	9.9	11.5	13.0
Scotland	5.1	7.8	8.7	9.0	12.8	14.2	12.5	11.1	12.3	12.1	11.4	14.0	13.6	15.0	25.0	23.6	25.4	23.7	13.9	12.8	16.4	15.5	16.3
Others (include in Faroe)	1.6	3.4	2.5	2.1	2.1	1.2	1.9	0.8	1.4	2.3	3.6	4.3	5.2	3.8	6.3	8.8	6.8	8.0	11.2	15.1	8.8	3.8	8.7
Total	23.8	34.8	31.9	32.5	43.5	52.2	49.1	27.9	43.6	45.2	47.4	52.5	62.4	57.2	90.8	95.3	78.7	77.9	73.8	77.2	54.9	43.5	63.2
	NORTH-WEST GREENLAND (6)																						
Faroe										39.6	32.2	13.0	21.7	14.5	40.3	27.5	52.1	36.2	34.8	46.9	54.7	40.1	30.1*
France										12.9	13.2	11.9	13.9	20.9	13.2	21.2	26.5	27.3	20.9	25.4	24.1	26.5	19.9*
Germany										4.7	7.3	3.9	9.8	5.8	6.1	36.0	38.9	43.2	34.7	41.2	29.3	66.9	50.3*
Norway										38.2	28.5	4.1	12.1	5.6	14.0	14.5	16.7	10.6	11.4	15.2	21.7	28.5	21.4*
Portugal										7.0	22.7	21.1	31.3	24.8	19.9	25.6	29.8	25.9	21.5	23.3	24.9	39.5	29.7*
Spain										1.6	6.7	7.6	8.8	8.0	2.6	0.8	1.8	0.1	0.2	0.5	1.1	4.8	3.6*
England										1.5	1.4	0.4	1.5	1.8	3.1	2.7	5.5	7.5	6.6	5.6	7.0	9.3	7.0*
USSR															1.1			5.0		0.8	0.8	0.4	1.0*
Dummy 1										47.1	36.5	14.3	16.1	7.1	13.0	5.0			2.7	12.2	24.3	16.8	6.0*
Total										152.6	148.5	76.3	115.2	88.5	113.3	133.3	171.3	155.8	132.8	171.1	187.9	232.8	169.0*

* Estimated values

APPENDIX 3 (*continued*)

	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968
SOUTH-WEST GREENLAND (7)																							
France										0.2	0.3	2.5	0.5	0.7	0.0	0.2	0.0	0.3	0.4	1.3	0.9	0.7	0.9*
Germany										0.2	0.5	0.3	2.9	1.0	3.1	15.0	18.7	20.1	15.8	12.2	14.0	16.9	21.7*
Norway										4.8	5.1	4.2	8.8	6.2	11.2	11.2	2.3	6.1	7.5	5.5	6.2	4.2	5.4*
Portugal											0.4	4.1	4.2	2.5	1.8	0.2	1.5	0.5		0.0	0.1		5.4*
Spain											0.4	1.6	1.3	0.9	0.1	0.0	0.3	0.0	0.1		0.0	1.6	2.0*
England										1.3	0.6	3.7	4.4	3.8	6.3	2.2	4.5	6.9	8.7	3.1	5.3	2.7	3.5*
USSR															0.0			0.5					1.0*
Dummy 2										0.1	4.0	6.7	13.4	11.5	20.8	28.7	32.2	26.8	19.2	12.6	5.9	5.1	10.0*
Total										6.6	11.3	23.1	35.5	26.6	43.3	57.5	59.5	61.2	51.7	34.7	32.4	31.2	49.9*
EAST GREENLAND (8)																							
Germany													5.8	14.1	21.6	18.7	14.6	19.4	29.5	24.8	16.8	18.2	19.6*
England															0.2	0.7	1.0	1.1	1.1	1.0	0.3	2.1	2.2*
Dummy 3													4.9	6.9	5.2	4.8	1.3	11.8	3.8	12.6	10.5	16.8	18.2*
Total													10.7	21.0	27.0	24.2	16.9	32.3	34.4	38.4	27.6	37.1	40.0*
LABRADOR/NEWFOUNDLAND (9)																							
France										3.8	6.5	6.5	11.8	12.9	30.0	28.9	22.2	23.3	27.9	22.2	30.1	30.4	39.6*
Germany															1.5	5.2	0.2	0.8	4.1	12.1	20.3	18.8	24.5*
Portugal										7.1	6.5	4.6	9.7	17.5	24.2	31.7	30.6	40.5	37.2	36.0	20.7	37.8	49.3*
Spain										0.0	0.2	0.6	6.9	18.2	21.0	29.1	28.0	27.6	32.2	36.5	29.4	26.8	34.9*
England														1.3	1.0	0.7	1.8	0.4	1.9	7.1	9.9	10.1	13.2*
USSR															137.8	101.9	61.7	29.4	58.5	44.3	36.3	17.2	80.0*
Dummy 4										43.3	45.5	49.9	48.7	61.1	38.3	29.2	30.4	36.8	43.9	57.3	94.2	89.0	90.0*
Total										54.2	58.7	61.6	77.1	111.0	253.8	226.7	174.9	158.8	205.7	215.5	240.9	230.1	331.5*

* Estimated values

	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968
	GRAND BANK (10)																						
Faroe												2.2	4.4	6.4	7.3	3.8	3.1	7.0	11.9	7.3	8.7	8.2	8.7*
France															8.8	6.9	12.0	6.2	15.6	16.6	15.2	13.4	14.1*
Germany															0.1	0.0			0.1	6.0	4.0	0.5	
Norway											0.8	12.0	7.1	3.4	3.4	2.1	1.2	2.5	3.7	0.0		2.1	2.3*
Portugal										30.8	26.0	29.8	17.7	23.2	26.1	19.7	14.1	18.7	30.2	23.1	23.4	47.0	49.7*
Spain										41.7	38.0	45.2	42.2	40.9	35.7	37.0	35.0	32.2	39.4	49.2	49.7	73.1	77.4*
England											0.8	0.3		1.0	4.5	2.8	2.3	5.0	7.2	12.5	9.5	13.4	14.2*
USSR															57.9	36.1	11.1	23.5	8.5	42.1	78.1	65.1	45.0*
Dummy 5										101.1	85.5	85.5	93.8	87.9	78.1	57.5	55.6	38.4	51.9	45.2	34.2	32.4	33.0*
Total										173.6	151.1	175.0	165.2	162.8	221.9	165.9	134.4	133.5	168.5	202.0	222.8	255.2	244.4*

* Estimated values.

APPENDIX 4 *National fishing effort in the north Atlantic (1946–68)* (million ton-hours' fishing)*

	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968 (est.)
Faroe	13.6	20.8	25.5	21.7	23.7	24.4	25.2	16.4	20.7	65.9	64.1	53.2	66.2	45.9	92.9	103.4	104.2	91.1	100.5	112.0	117.2	69.3	79.0
France										16.9	20.0	21.0	26.3	34.5	52.1	57.2	60.8	57.0	64.9	65.5	70.4	70.9	74.5
Germany	15.0	24.6	40.1	60.1	75.2	85.7	100.6	96.7	99.2	100.3	101.8	100.3	107.6	97.2	119.1	149.1	137.5	148.7	152.6	175.9	164.7	148.4	149.2
Norway	59.9	112.9	91.4	80.1	168.4	221.4	270.5	210.5	183.8	300.9	334.4	344.9	415.9	389.8	403.3	430.2	319.7	304.5	295.4	339.5	333.1	368.2	368.7
Portugal										44.9	55.6	59.6	62.9	68.1	72.1	77.3	76.1	85.6	89.0	82.4	105.0	124.3	134.1
Spain										43.4	45.3	55.1	59.3	68.1	59.4	66.9	65.1	59.9	71.8	86.3	86.5	106.3	117.9
England	81.2	149.5	195.2	210.1	243.4	289.7	273.4	234.4	247.3	248.3	254.6	292.8	318.5	328.8	368.6	363.3	386.5	400.8	404.3	393.3	351.7	355.6	320.7
USSR	52.5	74.0	88.4	95.4	108.0	137.5	156.8	171.0	208.8	224.2	318.0	292.8	310.0	302.4	542.5	625.4	581.1	534.1	375.6	324.7	391.0	382.7	602.6
Scotland	5.1	7.8	8.7	9.0	12.9	14.2	12.5	11.1	13.1	12.8	13.0	15.1	14.9	16.2	26.7	29.0	32.9	32.7	26.2	26.7	13.9	20.7	19.5
Belgium									3.8	5.4	6.0	6.3	7.0	5.4	7.3	8.4	1.3	8.6	6.8	7.8	6.8	3.4	3.9
Dummy 1										47.2	36.5	14.3	16.1	7.1	13.0	5.0			2.7	12.3	24.3	16.8	6.0
Dummy 2										0.1	4.0	6.7	13.4	11.5	20.8	28.7	32.2	26.8	19.2	12.6	5.9	5.1	10.0
Dummy 3													4.9	6.9	5.2	4.8	1.3	11.8	3.8	12.6	10.5	16.8	18.2
Dummy 4										43.3	45.5	49.9	48.7	61.1	38.3	29.2	30.4	36.8	43.9	57.3	94.2	89.0	90.0
Dummy 5										101.1	85.5	85.5	93.8	87.9	78.2	57.5	55.6	38.4	51.9	45.2	34.2	32.4	33.0
International fishing effort	227.3	389.6	449.3	476.4	631.6	772.9	839.0	740.1	776.7	1254.7	1384.3	1397.5	1565.5	1530.9	1899.5	2035.4	1884.1	1836.8	1708.6	1754.1	1809.4	1809.9	2027.3

* (1946–54) inclusive, effort refers to north-east Atlantic only. East Greenland starts in 1958; the other four stocks in the north-west Atlantic start in 1955.

APPENDIX 5 *The derivation of the yield model used in Section 3*

Consider the yield obtainable from a single year-class throughout its life.

Assume that recruits enter the fishery at 1 year of age.

1-year-olds suffer $(\varepsilon_1 F+M)$ mortality;

$$\therefore \text{catch of 1-year-olds } (C_1)=\frac{\varepsilon_1 F}{\varepsilon_1 F+M}\cdot R\left(1-e^{-(\varepsilon_1 F+M)}\right).w_1.$$

2-year-olds suffer $(\varepsilon_2 F+M)$ mortality;

$$\therefore \text{catch of 2-year-olds } (C_2)=\frac{\varepsilon_2 F}{\varepsilon_2 F+M}\cdot R\left(1-e^{-(\varepsilon_2 F+M)}\right)e^{-(\varepsilon_1 F+M)}.w_2.$$

Etc.

$$\therefore \sum_{i=1}^{12} C_1=R\sum_{i=1}^{12}\frac{\varepsilon_i F}{\varepsilon_i F+M}\cdot\left(1-e^{-(\varepsilon_i F+M)}\right)e^{-\sum_{j=1}^{i=1}(\varepsilon_j F+M)}.w_i.$$

APPENDIX 6 *Estimation of q: units of fishing effort, f, are in 10^6 ton-hours' fishing, giving units of q per 10^6 ton-hours' fishing*

	Barents Sea		Norway coast		Bear Island		Iceland		Faroe		Greenland						Labrador/ Newfoundland		Grand Bank	
											north-west		south-west		east					
	Z	f	Z	f	Z	f	Z	f	Z	f	Z	f	Z	f	Z	f	Z	f	Z	f
1946–47	0.34	150			1.25	43														
47–48	0.53	180			0.11	42														
48–49	0.47	211			1.94	38														
49–50	0.81	212			0.81	60														
50–51	0.47	294			1.13	70														
51–52	0.91	361			1.19	58														
52–53	1.17	319			0.95	53														
53–54	0.61	329			1.52	47														
54–55	0.43	409			1.01	59											0.54	59		
55–56	1.26	506			1.33	123	0.47	170									0.27	62		
56–57	0.87	456			1.24	182	0.84	220			0.24	76	0.97	23			1.04	77		
57–58	0.65	476			1.44	214	0.75	238			0.53	115	0.67	36			0.30	111		
58–59	0.74	388			0.92	259	0.84	207			0.98	89	0.15	27	0.03	21	0.16	254	1.99	222
59–60	1.56	548			2.13	131	0.86	234	0.91	91	0.19	113	1.28	43	1.53	27	−0.17	227	−0.38	166
60–61	0.66	602			0.66	215	0.54	254	1.27	95	0.55	133	0.16	57	−0.26	24	1.19	175	0.04	134
61–62	0.99	603			0.84	173	0.66	265	0.80	79	0.53	171	0.19	60	0.85	17	0.57	159	0.67	134
62–63	1.30	616			1.62	124	0.64	304	0.82	78	0.74	156	1.07	61	0.74	32	0.57	206	−0.22	169
63–64	1.06	391			0.99	189	1.19	331	0.78	74	0.22	133	0.20	52	0.35	34	0.02	215	0.60	202
64–65	1.51	436			1.26	130	0.65	337	0.57	77	1.16	171	0.49	35	1.71	38	0.56	241	1.97	223
65–66	0.89	490			1.19	149	0.84	285	0.46	68			0.65	32	−0.18	28				
Average values of Z and f	0.86	399			1.17	118	0.75	258	0.80	80	0.57	128	0.56	43	0.58	28	0.45	162	0.51	179
Ages of fish over which Z's were obtained	6/7 to 10/11				6/7 to 11/12		5/6 to 11/12		3/4 to 7/8		6/7 to 10/11		8/9 to 12/13		9/10 to 14/15		8/9 to 14/15		6/7 to 14/15	
$\hat{q}$	0.00143						0.00166													
(S.E.)	(0.00049)						(0.00140)													
$\hat{M}$	0.29						0.32													
Significance of regression	95%				N.S.		N.S.		N.S.		N.S.		N.S.		N.S.		N.S.		N.S.	
$\bar{q}=\frac{\bar{F}}{\bar{f}}$ M=0.1	0.00190				0.00907		0.00252		0.00875		0.00367		0.01070		0.01714		0.00216		0.00229	
M=0.2	0.00165				0.00822		0.00213		0.00750		0.00289		0.00837		0.01357		0.00154		0.00173	
M=0.3	0.00140				0.00737		0.00174		0.00625		0.00211		0.00605		0.01000		0.00093		0.00117	
Resulting estimate of q	0.0016		0.0035		0.0050		0.0022		0.0075		0.0025		0.0100		0.0150		0.0017		0.0017	

N.S.=not significant.

APPENDIX 7 *Array AA: estimated numbers of cod (millions) aged 1 to 12 years in 10 stocks in 1946*

Stock	Age (years)											
	1	2	3	4	5	6	7	8	9	10	11	12
Barents Sea	0	506	698	517	293	132	65	62	152	55	32	56
Norway coast	0	0	0	0	0	0	0	0	0	0	0	0
Bear Island	0	159	246	249	142	65	30	30	74	28	13	28
Iceland	0	133	99	188	26	16	13	7	7	18	13	9
Faroe	0	7.7	6.3	5.2	4.2	3.4	2.8	2.3	1.9	1.5	1.3	3
North-west Greenland	0	391	95	104	163	45	40	117	17	10	7	3
South-west Greenland	0	80	31	34	54	15	13	39	5	3	2	1
East Greenland	0	29.3	17.9	10.9	6.6	3.8	2.4	1.6	0.7	0.6	0.5	0
Labrador/Newfoundland	0	500	500	500	443	269	164	99	59	36	25	13
Grand Bank	0	368	502	247	183	272	90	67	50	37	27	0

APPENDIX 8 *Array AB: average number, for all years from 1946 to 1968, of one-year-old cod recruiting in each of the 3 months September, October, November to the 10 stocks*

Stock	Average number ($\times 10^{-6}$)
Barents Sea	217
Norway coast	0
Bear Island	80
Iceland	56
Faroe	7
North-west Greenland	83
South-west Greenland	27
East Greenland	6
Labrador/Newfoundland	190
Grand Bank	150

APPENDIX 10 *Array AD: estimated number of ton-hours' fishing per trip by the 15 nation*

Nation	Estimated number (ton-hours)
Faroe	0.400
France	1.980
Germany	0.060
Norway	0.500
Portugal	1.200
Spain	1.000
England	0.084
USSR	0.100
Scotland	0.050
Belgium	0.040
Dummy 1	0.500
Dummy 2	0.500
Dummy 3	0.500
Dummy 4	0.500
Dummy 5	0.500

APPENDIX 9 *Array AC: national fishing effort (10⁻³ × hours fishing) in each year*

Nation	Year																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Faroe	1.13	1.73	2.13	1.81	1.98	2.03	2.10	1.37	1.73	5.50	5.34	4.43	5.52	3.83	7.74	8.62	8.68	7.59	8.37	9.33	9.77	5.77	6.58
France										1.41	1.67	1.75	2.19	2.88	4.34	4.77	5.07	4.75	5.41	5.46	5.87	5.91	6.21
Germany	1.25	2.05	3.34	5.01	6.27	7.14	8.38	8.06	8.27	8.36	8.48	8.36	8.97	8.10	9.93	12.43	11.46	12.39	12.72	14.66	13.72	12.37	12.43
Norway	4.99	9.41	7.62	6.68	14.03	18.45	22.54	17.54	15.32	25.08	27.87	28.74	34.66	32.48	33.61	35.85	26.64	25.38	24.62	28.29	27.76	30.68	30.72
Portugal										3.74	4.63	4.97	5.24	5.68	6.01	6.44	6.34	7.13	7.42	6.87	8.75	10.36	11.17
Spain										3.62	3.78	4.59	4.94	5.68	4.93	5.58	5.43	4.99	5.98	7.19	7.21	8.86	9.82
England	6.77	12.46	16.27	17.51	20.28	24.14	22.78	19.53	20.61	20.69	21.22	24.40	26.54	27.40	30.72	30.28	32.21	33.40	33.69	32.77	29.31	29.63	26.72
USSR	4.38	6.17	7.37	7.95	9.00	11.46	13.07	14.25	17.40	18.68	26.50	24.40	25.83	25.20	45.21	52.12	48.43	44.51	31.30	27.06	32.58	31.89	50.21
Scotland	0.43	0.65	0.73	0.75	1.08	1.18	1.04	0.93	1.09	1.07	1.08	1.26	1.24	1.35	2.23	2.42	2.74	2.73	2.18	2.22	1.16	1.72	1.62
Belgium									0.32	0.45	0.50	0.53	0.58	0.45	0.61	0.70	0.11	0.72	0.32	0.65	0.57	0.28	0.32
Dummy 1										3.93	3.04	1.19	1.34	0.59	1.08	0.42			0.22	1.02	2.20	1.40	0.50
Dummy 2										0.01	0.33	0.56	1.12	0.96	1.73	2.39	2.68	2.23	1.60	1.05	0.49	0.42	0.83
Dummy 3													0.41	0.58	0.43	0.40	0.11	0.98	0.32	1.05	0.87	1.40	1.52
Dummy 4										3.61	3.79	4.16	4.06	5.09	3.19	2.43	2.53	3.07	3.66	4.77	7.85	7.42	7.50
Dummy 5										8.43	7.13	7.13	7.82	7.33	6.52	4.79	4.63	3.20	4.32	3.77	2.85	2.70	2.75
Total	18.95	32.47	37.46	39.71	52.64	64.40	69.91	61.68	64.74	104.58	115.36	116.47	130.46	127.60	158.28	169.64	157.06	153.07	142.38	146.17	150.78	150.82	168.93
Annual total (=total×12)	227	390	450	477	632	773	839	740	777	1255	1384	1398	1566	1531	1899	2036	1885	1837	1709	1754	1809	1809	2027

APPENDIX 11 *Array AE: biological parameters of the 10 stocks: parameters 1–12 are* ε_i *(i=ages 1 to 12 years), parameters 13–24 are* W_i *in grammes (i=1 to 12), parameter 25 is* $\overline{M}$ *per month*

Stock	Parameter																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Barents Sea	0	0	0	0.3	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	93	259	480	850	1 220	1 980	2 740	3 670	4 800	6 560	8 190	10 070	0.0083
Norway coast	0	0	0	0	0	0	0.05	0.2	0.5	1.0	1.0	1.0	93	259	480	850	1 220	1 980	2 740	3 670	4 800	6 560	8 190	10 070	0.0083
Bear Island	0	0	0	0.15	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	93	259	480	850	1 220	1 980	2 740	3 670	4 800	6 560	8 190	10 070	0.0083
Iceland	0	0.03	0.3	0.85	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	33	260	760	1 530	2 520	3 720	5 100	6 540	8 230	9 660	11 200	12 800	0.0167
Faroe	0.03	0.45	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	320	980	1 960	3 150	4 450	5 750	6 990	8 190	9 250	10 170	10 960	11 700	0.0167
North-west Greenland	0	0	0.05	0.45	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	65	390	970	1 710	2 510	3 310	4 030	4 690	5 250	5 740	6 120	6 460	0.0167
South-west Greenland	0	0	0	0.05	0.4	0.7	1.0	1.0	1.0	1.0	1.0	1.0	9	100	329	711	1 238	1 887	2 643	3 463	4 304	5 195	6 077	6 960	0.0167
East Greenland	0	0	0	0.05	0.15	0.3	0.6	1.0	1.0	1.0	1.0	1.0	193	525	1 017	1 622	2 316	3 052	3 781	4 529	5 244	5 913	6 552	7 124	0.0167
Labrador/Newfoundland	0	0	0.05	0.20	0.55	0.80	1.0	1.0	1.0	1.0	1.0	1.0	2	39	158	466	865	1 286	1 690	2 047	2 359	2 604	2 820	2 988	0.0167
Grand Bank	0	0	0.15	0.6	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2	39	176	489	945	1 492	2 084	2 708	3 310	3 908	4 460	4 961	0.0167

APPENDIX 12 *Array AF: economic weighting factors for 15 nations and 10 stocks (arbitrary units)*

Stock	Nation														
	Faroe	France	Germany	Norway	Portugal	Spain	England	USSR	Scotland	Belgium	Dummy 1	Dummy 2	Dummy 3	Dummy 4	Dummy 5
Barents Sea	0	0	91	90	0	0	91	90	0	0	0	0	0	0	0
Norway coast	0	0	88	93	0	0	88	0	0	0	0	0	0	0	0
Bear Island	0	0	76	71	0	0	76	71	0	0	0	0	0	0	0
Iceland	122	0	116	122	0	0	116	0	116	100	0	0	0	0	0
Faroe	154	0	0	0	0	0	152	0	152	0	0	0	0	0	0
North-west Greenland	44	56	44	44	56	56	44	0	0	0	100	0	0	0	0
South-west Greenland	0	62	49	49	62	0	49	0	0	0	0	100	0	0	0
East Greenland	0	0	126	0	0	0	0	0	0	0	0	0	100	0	0
Labrador/Newfoundland	0	55	44	0	55	55	0	44	0	0	0	0	0	100	0
Grand Bank	82	91	0	0	91	91	82	82	0	0	0	0	0	0	100

NDIX 13 *Array AG: monthly values of q (per 10^8 ton-hours' fishing) for the 10 stocks*

	Month												Average annual q
	1	2	3	4	5	6	7	8	9	10	11	12	
; Sea	0.15	0.13	0.18	0.19	0.19	0.21	0.19	0.18	0.13	0.11	0.13	0.17	0.16
y coast	0.58	0.56	0.45	0.68	0.33	0.35	0.35	0.25	0.19	0.12	0.13	0.22	0.35
land	0.41	0.37	0.32	0.57	0.72	0.80	0.63	0.57	0.39	0.32	0.41	0.49	0.50
	0.15	0.23	0.24	0.25	0.30	0.30	0.25	0.21	0.21	0.18	0.15	0.16	0.22
	0.89	0.85	1.65	1.58	0.93	0.97	0.87	0.86	0.88	0.94	0.84	0.75	1.00
west Greenland	0	0.08	0.19	0.09	0.43	0.45	0.19	0.30	0.25	0.26	0.27	0.50	0.25
west Greenland	1.09	1.31	0	0	0.92	0.95	0.46	0.93	1.09	0.88	1.24	1.13	1.00
reenland	1.63	1.97	0	0	1.38	1.42	0.69	1.40	1.64	1.33	1.87	1.69	1.50
lor/Newfoundland	0.04	0.08	0.10	0.20	0.23	0.25	0.14	0.21	0.18	0.19	0.22	0.20	0.17
Bank	0	0	0.16	0.28	0.19	0.21	0.16	0.09	0.13	0.15	0.18	0.16	0.17

Appendix 14

```
      DØC ECMC-10
      SHØRT LIST(LP)
      PRØGRAM(ECMC)
      INPUT 2=TRO
      ØUTPUT 4=LPO/160
      CØMPACT DATA
      TRACE
      END
      MASTER ECMC
      DIMENSIØN AA(10,12),AB(10,21),AC(15,21),AD(15),AE(10,25),AF(10,1
     1,AG(10,12),ANSC(15,10),ANSF(15,10),CPD(10),FMIL(15,10),STØNE(20)
     2  STTWØ(20),TITLE(6),NATIØN(2,15),SURV(3),JØB(3)
      DATA STØNE(1)/16OH   BARENTS          NØRWAY            BEAR
     1   ICELAND          FARØES         NØRTH-WEST          SØUTH
     2  EAST           LABRADØR-          GRAND        /
      DATA STTWØ(1)/16OH     SEA             CØAST          ISLAND
     1                                     GREENLAND       GREENLAND
     2GREENLAND     NEWFØUNDLAND          BANKS        /
      DATA TITLE(1)/48H   NATIØN             TØTAL            AGE
101   FØRMAT(3IO)
102   FØRMAT(15F0.0)
103   FØRMAT(A8,A4,F0.0)
104   FØRMAT(3A8)
150   FØRMAT(1H1)
151   FØRMAT(1H ,31HNØRTH ATLANTIC EFFØRT - MØDEL 2,25X,3A8,50X,8HPAGE
     1Ø.,13/)
152   FØRMAT(1H ,45HDISTRIBUTIØN ØF EFFØRT (MILLIØN TØN HØURS) IN,15/
     1  51X,5HSTØCK)
153   FØRMAT(1H ,47HDISTRIBUTIØN ØF CATCH (THØUSAND METRIC TØNS) IN,15
     1  51X,5HSTØCK)
154   FØRMAT(1H ,39HAGE CØMPØSITIØN ØF STØCKS (MILLIØNS) IN,I5/51X,
     1  5HSTØCK)
158   FØRMAT(1H ,I6,6X,10(F9.3,4X))
159   FØRMAT(1H ,5HTØTAL,7X,11(F9.1,4X))
160   FØRMAT(1H )
155   FØRMAT(1H ,A8,A4,11(A8,A5))
156   FØRMAT(1H ,12X,10(A8,A5))
157   FØRMAT(1H ,A8,A4,11(F9.1,4X))
      WRITE(4,150)
      READ(2,104) (JØB(I),I=1,3)
      READ(2,101) IN,IS,ITM
      DØ 3 I=1,IS
3     READ(2,102)(AA(I,J),J=1,12)
      DØ 6 I=1,ITM
6     READ(2,102) (AB(J,I),J=1,IS)
      DØ 9 I=1,ITM
9     READ(2,102) (AC(J,I),J=1,IN)
      DØ 12 I=1,IN
12    READ(2,103) (NATIØN(J,I),J=1,2),AD(I)
      DØ 15 I=1,25
15    READ(2,102) (AE(J,I),J=1,IS)
      DØ 18 I=1,IN
18    READ(2,102) (AF(J,I),J=1,IS)
      DØ 21 I=1,12
21    READ(2,102) (AG(J,I),J=1,IS)
      DØ 95 IT=1,ITM
      DØ 30 L=1,IN
      DØ 29 M=1,IS
29    ANSC(L,M),ANSF(L,M)=0.0
30    CØNTINUE
      DØ 70 L=1,12
```

dix 14 (*continued*)

```
      IF(L.LT.9.ØR.L.GT.11) GØ TØ 33
      DØ 32 I=1,IS
      AA(I,1)=AA(I,1)+AB(I,IT)
      DØ 46 M=1,IN
      SCPD,SCWIJ=0.0
      DØ 44 I=1,IS
      IF(IT.GT.9.ØR.I.LE.5) GØ TØ 35
      CPD(I)=0.0
      GØ TØ 44
      FM=AD(M)*AG(I,L)
      DØ 40 J=1,12
      IF(I.EQ.2) AA(2,J)=AA(1,J)+AA(3,J)
      SCWIJ=SCWIJ+AA(I,J)*AE(I,J)*AE(I,J+12)*FM
      CPFI=SCWIJ/AD(M)
      CPD(I)=CPFI*AF(I,M)
      SCPD=SCPD+CPD(I)
      SCWIJ=0.0
      DØ 46 I=1,IS
      FRCT=CPD(I)/SCPD
      STF=FRCT*AC(M,IT)
      ANSF(M,I)=ANSF(M,I)+STF
      FMIL(M,I)=STF*AG(I,L)
      DØ 65 J=1,12
      DØ 60 I=1,IS
      EFF=AE(I,25)
      DØ 48 M=1,IN
      EFF=EFF+FMIL(M,I)*AE(I,J)
      DØ 50 M=1,IN
      ANSC(M,I)=ANSC(M,I)+AA(I,J)*AE(I,J)*FMIL(M,I)*AE(I,J+12)*(1.0-
     1  EXP(-EFF))/EFF
      IF(I.LE.3) GØ TØ 55
      IF(IT.LE.9.AND.I.GT.5) GØ TØ 60
      AA(I,J)=AA(I,J)*EXP(-EFF)
      GØ TØ 60
      SURV(I)=AA(I,J)*EXP(-EFF)
      IF(I.LT.3) GØ TØ 60
      AA(1,J)=SURV(1)-AA(1,J)*(AA(2,J)-SURV(2))/AA(2,J)
      AA(3,J)=SURV(3)-AA(3,J)*(AA(2,J)-SURV(2))/AA(2,J)
      AA(2,J)=0.0
      CØNTINUE
      CØNTINUE
      CØNTINUE
      WRITE(4,151) (JØB(I), I=1,3), IT
      JT=1945+IT
      WRITE(4,152) JT
      KS=IS
      IF (IT.LE.9.AND.IS.GT.5).KS=5
      WRITE(4,155) (TITLE(I),I=1,2),((STØNE(J),J=2*I-1,2*I),I=1,KS)
     1  (TITLE(I),I=3,4)
      WRITE(4,156) ((STTWØ(J),J=2*I-1,2*I),I=1,KS)
      DØ 75 L=1,IN
      TØT=0.0
      DØ 72 M=1,KS.
      TØT=TØT+ANSF(L,M)
      WRITE(4,157) (NATIØN(I,L),I=1,2),(ANSF(L,M),M=1,KS),TØT
      TØT=0.0
      DØ 80 M=1,KS
      CPD(M)=0.0
      DØ 77 L=1,IN
      CPD(M)=CPD(M)+ANSF(L,M)
      TØT=TØT+CPD(M)
```

Appendix 14 (*continued*)

```
      WRITE(4,159) (CPD(M),M=1,KS),TØT
      WRITE(4,160)
      WRITE(4,153) JT
      WRITE(4,155) (TITLE(I),I=1,2),((STØNE(J),J=2*I-1,2*I),I=1,KS)
     1  (TITLE(I),I=3,4)
      WRITE(4,156) ((STTWØ(J),J=2*I-1,2*I),I=1,KS)
      DØ 85 L=1,IN
      TØT=0.0
      DØ 82 M=1,KS
      ANSC(L,M)=ANSC(L,M)/1000.0
82    TØT=TØT+ANSC(L,M)
85    WRITE(4,157) (NATIØN(I,L),I=1,2),(ANSC(L,M),M=1,KS),TØT
      TØT=0.0
      DØ 90 M=1,KS
      CPD(M)=0.0
      DØ 87 L=1,IN
87    CPD(M)=CPD(M)+ANSC(L,M)
90    TØT=TØT+CPD(M)
      WRITE(4,159) (CPD(M),M=1,KS),TØT
      WRITE(4,160)
      WRITE(4,154) JT
      WRITE(4,155) (TITLE(I),I=5,6),((STØNE(J),J=2*I-1,2*I),I=1,KS)
      WRITE(4,156) ((STTWØ(J),J=2*I-1,2*I),I=1,KS)
      DØ 92 I=1,12
92    WRITE(4,158) I,(AA(J,I),J=1,KS)
      DØ 94 I=1,KS
      DØ 93 J=1,11
93    AA(I,13-J)=AA(I,12-J)
94    AA(I,1)=0.0
      NLINE=36-2*IN
      DØ 95 J=1, NLINE
      WRITE(4,160)
95    CØNTINUE
      PAUSE 77
      END
      FINISH
```